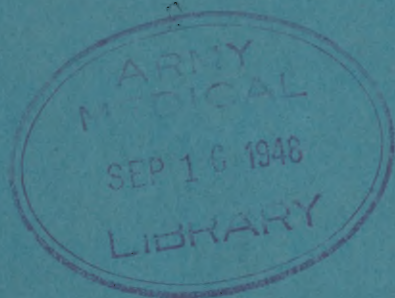


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**THE BIOPHYSICAL REQUIREMENTS FOR
VENTILATED CLOTHING**



**UNITED STATES AIR FORCE
AIR MATERIEL COMMAND
Wright-Patterson Air Force Base
Dayton, Ohio**

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WAR DEPARTMENT
UNITED STATES AIR FORCE
HEADQUARTERS
AIR MATERIEL COMMAND

U. S. AIR FORCE TECHNICAL REPORT
No. 5702

THE BIOPHYSICAL REQUIREMENTS FOR
VENTILATED CLOTHING

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SUMMARY

The purposes of this report are to establish the principles for engineering development of ventilated clothing and define the ventilation requirements for a wide temperature range; to record new observations upon temperature regulation of the extremities and relate these findings to ventilated and electrically heated clothing.

The following conclusions are reached:

1. Forced, internal ventilation of clothing offers a practical and economical means of thermal protection in hot environments, in environments which vary between hot and cold, and in environments which require impermeable outer clothing; provided that an air supply hose may be attached to the wearer.
2. Ventilated clothing permits choice of protective and/or insulative garments on the basis of functional suitability alone, since no thermal stress is imposed on the wearer.
3. Orderly engineering development is feasible on the basis of the principles and requirements set forth herein.
4. The hands and feet require no artificial heating or cooling in the range between -30° F. and $+180^{\circ}$ F., if prolonged contact with good conductors is avoided. With ventilated clothing, it is better to err on the side of over-heating, rather than of over-cooling the body to insure protection of the extremities at very high or low temperatures.
5. The power distribution of the present standard electrically heated clothing requires re-examination.

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I. INTRODUCTION

A. The Problem of the Air Force.

Neither physiological regulation nor insulative clothing can protect man exposed to a wide range of rapidly changing temperatures, or to very high temperatures. These conditions are of common occurrence in operations of the Air Force. Aircraft may take off in temperatures of 90° F. and, within an hour, fly in air of -60° F. Furthermore, high cabin temperatures occur in very fast aircraft.

If an aircraft is adequately heated, the crew will be comfortable in clothing designed for "room" temperature. However, if the crew must abandon the aircraft on a cold ocean or arctic terrain, such clothing will be inadequate for survival. If heavier clothing or an anti-exposure suit is worn in a heated aircraft, sweating will occur. This results not only in discomfort, but the accumulation of sweat in clothing lowers its insulation. If the aircraft is not heated, the men will wear heavy clothing and will sweat before the cabin temperature drops; then, when the cabin becomes very cold, no amount of clothing compatible with satisfactory performance is sufficient to keep them warm. The electrically heated suit is a partial answer to the problem of protection at temperatures between about 30° F. and -40° F. However, if it is worn with outer clothing chosen for survival in the cold, sweating will occur before the cabin temperature falls. There is no clothing in present use which, in combination with the aircraft heating or cooling system, will allow the man to remain comfortable over the wide range of rapidly changing temperatures encountered in Air Force operations; and which will be suitable for survival on the terrain over which the crew is to fly.

A means of solving these problems is to blow conditioned air under the clothing near the skin, i. e., to replace the ambient environment with an individual environment. This inner environment can be kept constant over a wide range of ambient temperatures by regulation of the flow and temperature of the ventilating air, to compensate for heat leakage through the outer clothing. Requirements for cabin temperature control equipment might be reduced considerably, since the space to be conditioned would be reduced to roughly one cubic foot per man. The principal limitation of the method is the dependency of the man upon a connection to a source of conditioned air.

B. History.

The idea of blowing or circulating air underneath clothing is not new. A patent was filed in 1904 for a "Body Ventilating Apparatus" (1). It is within the last several years, however, that its feasibility has been investigated. Houghten, et al. (2) in 1941, increased workers'

INTRODUCTION

tolerance and efficiency in hot environments by use of an internally ventilated coverall. Their report outlined some of the physical principles of the problem. Ventilated clothing was further studied during World War II. An Australian group designed and tested a ventilating harness and air supply system for use in tanks at ambient temperatures of about 100° F. During the period 1943-1945 the Armored Medical Research Laboratory reported the experimental use of a ventilated garment designed for use in tanks (3). The Royal Canadian Air Force began work on an air-heated undersuit in 1942. By 1945 one had been developed which gave reasonable protection against temperatures down to -30° C., as judged by subjective comfort and skin temperature measurements (4).

The first tests of ventilated clothing by the Aero Medical Laboratory, Engineering Division, were described in 1945 (5). These were undertaken to develop a suit for the protection of men doing moderate work at 165° F. The garment was intended for use in the Climatic Hangar of the Air Force Proving Ground Command.

C. The Rationale of the Present Study.

The previous studies of internal ventilation of clothing have been principally tests of a particular item of equipment intended for a specific use. No sufficient analysis has been made of either the physical and physiological requirements, or the potentialities of forced ventilation as a solution to the Air Force problem. The present study is an attempt to define the requirements for rational engineering of ventilated clothing. The report is concerned with what any system must do to provide comfort with variation of the ambient temperature, amount of outer clothing, and activity of the man. It is not concerned with the mechanics of the system. (A few suggestions arising from our experience are offered incidentally in Section VII.) A preliminary analysis has been reported earlier (6).

The experiments discussed herein were designed to keep men comfortable at ambient temperatures from -30° to +180° F., when clothing designed for use at about 50° F. was worn. Since they were planned to maintain comfort, no control experiments were required; and the difficult problem of a sound definition of tolerance, with its inherent time factor, was avoided.

II. THEORETICAL CONSIDERATIONS.

A. General

The general relation between the rate of heat uptake of the ventilating air, the rate of heat production of the body, the rate of heat leakage through the clothing, and the rate of change of the heat content of the body may be written:

$$\Delta H_v/t = Q_b/t - Q_g/t - \Delta H_b/t \quad (1)$$

Where:

ΔH_v is the change in heat content (enthalpy) of the ventilating air. This is taken as positive when the heat content of the air increases.

Q_b is the sensible heat production of the body; i.e., the difference between the total metabolic heat and evaporative heat loss.

Q_g is the heat leakage through the clothing. This is taken as positive when the direction of heat flow is outward.

ΔH_b is the change of heat content of the body. Contrary to some terminology, this is defined as being positive when the heat content of the body increases. And,

t is time.

The difference $Q_b - Q_g$ is termed the steady state heat surplus, Q_s . It is the heat which must be moved from the system to maintain its thermal equilibrium. At high ambient temperatures, when Q_g is negative Q_s is positive; that is, the heat to be removed is the sensible heat minus the negative heat leakage through the clothing. In the cold, Q_g is positive and Q_s , negative.

The kernel of the problem is the determination of $\Delta H_v/t$ for any combination of insulative clothing, ambient temperature, and activity. The terms ΔH_v and Q_g are the physical, and Q_b and ΔH_b are the physiological variables.

B. Physical Considerations

1. The Ventilating Air. The rate of increase in heat content of the ventilating air, $\Delta H_v/t$, is defined by the equation:

$$\Delta H_v/t = (W_v/t) C_v (T_{v2} - T_{v1}) \quad (2)$$

Where:

W_v/t is the flow rate of the air in weight units per unit time.

C_v is the specific heat of the air at constant pressure.

T_{v1} and T_{v2} are the temperatures of the air entering and leaving the garments respectively.

(Variation of the humidity of the ventilating air is of little importance since its effect upon C_v is well within the limits of experimental error. Furthermore, the inlet air may be fully saturated and yet evaporate the insensible perspiration, provided its temperature is slightly below skin temperature).

To make the best use of the ventilating air with a given thickness of clothing, there should be a minimum of insulation between the skin and the ventilating air. Furthermore, the longer the ventilating air is in contact with the system, the more complete will be the heat exchange. The air should flow parallel to the skin and not transversely through the outer clothing.

2. The Heat Exchange Through the Clothing. The rate of heat exchange through the clothing, Q_g/t , is determined by the insulation of the clothing worn over the ventilating air, and by the environmental conditions. This relation may be expressed by the clo equation of Gagge, Burton, and Bazett (7) in a slightly modified form:

$$Q_g/t = \frac{k_g A_c (T_c - T_o)}{I} \quad (3)$$

Where:

k_g is the constant for conversion to clo.

A_c is the area of the clothing layer just outside the ventilating air, i.e., of the barrier coverall described below.

T_c is the average barrier coverall temperature.

T_o is the operative temperature (8).

I is the insulation (in clo) of the outer clothing plus the insulation of the ambient air, i.e.,

$$I = I_g + I_a \quad (4)$$

The definition of clo involves the subtraction of the insulation of the air from the total insulation (7), which implies that the unit is additive. However, since clo is defined as a temperature difference per unit rate of heat production per unit area, it is strictly additive only if increased thickness of insulation does not change the outer area, i.e., for flat surfaces. The usual practice is to determine I_g and I_a separately; I_g from human or copper man measurements (9) and I_a from an empirical equation (10) such as:

$$I_a = \frac{I}{0.61 \times (T/298)^2 + 0.19 \sqrt{V} \times 298/T} \quad (5)$$

Where:

T is the temperature of the ambient air in °K.

V is the rate of air movement in cms. per second.

This procedure has been followed in the calculations to be described. The insulation of the outer clothing was determined upon the electrically heated copper manikin (9) with the clothing layer immediately over the ventilating air next to the heated surface of the manikin. It is to be noted that when the requirements established by these experiments are used, insulation must be determined in a like manner. The error in the addition of I_a and I_g is due to the variation of outer clothing area with different clothing assemblies. The absolute value of this error increases with increasing thickness of the clothing, but since I_a is small compared to I_g , the relative error may decrease with heavier clothing. It probably is never greater than 10%.

The temperature and the area of the barrier coverall, rather than of the skin, are used in equation (3) because the outer clothing primarily insulates the air, and not the man, from the environment. It is obvious from equations (1) and (3) that $\Delta H_v/t$ will vary inversely with the insulation. The rate of heat leakage through the clothing becomes large when T_o differs significantly from T_c . When the man is comfortable, T_c is relatively constant over the wide range of ambient temperatures studied.

There are several factors which are not considered in equations (1) and (2) because they are within the limits of error of the experiments to be described. These are the change in heat content of the clothing, the change in kinetic energy of the ventilating air, and any Joule-Thompson effect.

C. Physiological Considerations

The rate of sensible heat production of the body, Q_b/t , is defined by the equation:

$$Q_b/t = Q_m/t - Q_e/t \quad (6)$$

Where:

Q_m/t is the rate of metabolic heat production.

Q_e/t is the rate of evaporative heat loss.

Whether or not a given physiological adjustment causes discomfort may depend upon the experimental conditions. Thus, while accumulation of sweat in clothing is uncomfortable, moderately increased sweating in a ventilated system is not, since evaporation is rapid to the internally circulating air. The subjective effect of vasoconstriction in the hands and feet depends upon whether or not these parts are included within the ventilating air circuit. A rate of change of stored body heat of ± 10 Cal./hr. usually produces no discomfort.

In a physical system, a given $\Delta H_v/t$ can be achieved by wide variation of both the air flow and temperature. In a physiological system, the temperature range of the ventilating air is limited. Air hot enough to raise skin temperature to 120° F. will produce hyperemia in 8 minutes and epidermal necrosis in 10 minutes. When skin temperature is 111° F., hyperemia occurs in 5 hours, and epidermal necrosis in 6 (11). Discomfort due to chilling at the ventilating air inlet openings will result if very cold air is used.

III. METHODS

A. Experimental

1. Conditions. The experiments were conducted at about 180, 120, 75, 0, -20 and -30° F. in the All-Weather Room of the Aero Medical Laboratory. There was no significant difference between air and wall temperatures. When the room was cold, air movement around the subject was no greater than 70 ft./min. ($I_a = 0.7$ clo); when the room was hot, air movement was less than 15 ft./min. ($I_a = 0.8$ clo). Since sweat was evaporated only to the ventilating air, the humidity of the ambient air was not considered. Operative temperature was the same as dry bulb temperature.

2. The Ventilating Air. The ventilating air was supplied from a compressed air line. A separate inlet hose was provided for each body region. In each, flow rate was metered by a rotameter, and corrected to one atmosphere and 70° F. Inlet air temperature, controlled by passing the air through copper coils submerged in a water bath, was measured at the entrance to the clothing and helmet. The water content of the air was low, varying from 0.01 to 0.02 lbs./lb. The amount of air supplied to each region was roughly proportional to its area (13% to each arm, 25% to each leg, 24% to the trunk).

3. The Ventilating Assembly. It was not relevant, at this stage, to compare existing models of ventilating harnesses, or to fashion anything more than a garment for experimental purposes. A ventilating assembly was designed to give reasonably good air distribution, and so that the temperature of the air leaving the clothing (outlet air temperature could be measured. Use of a single air outlet was not feasible because of ballooning of the clothing from back pressure. Therefore a coverall was made which divided the body into trunk, arm and leg regions; flow rate, inlet and outlet air temperatures were measured separately for each. The assembly consisted of six rubber tubes of 1/2 inch internal diameter supported on a thin, air impermeable barrier coverall. Each tube began at the left side at the mid-trunk, attaching there, by a coupling, to its supply line. One tube ended at the shoulder in a coupling for the helmet. Another, supplying the trunk, pierced the coverall to encircle the waist; it was provided with several small holes, spaced and sized so as to distribute the air evenly. The tubes to the arms and legs opened a few inches below the elbows and knees. The air, confined by the coverall, flowed parallel to the skin surface. It was insulated from the

skin only by the thermocouple underwear, 0.28 clo, except over the trunk, where a Brynje vest was also worn as a spacer.

An outlet opening of 1-1/2 inch diameter was cut in each area of the coverall. The outlets for the extremities were located at the upper arms and legs. The trunk outlet was at the right nipple. Openings were cut in corresponding positions in the outer clothing. A free channel from beneath the coverall to the outside was assured by plastic chimneys fitted into the openings. These also prevented air from leaking into the outer layers of the clothing. Drawstrings at the axillae and groin precluded mixing of air from different regions. Tight wristlets and anklets prevented air from escaping at these points. Since escape of significant amounts of air from other than designated outlets could not occur, valid outlet air temperatures were obtained from thermocouples placed in these openings.

A helmet covering head and neck was constructed with an insulation equivalent to 0.9 clo. It was suspended from a wire frame so that an air space separated the head from its inner lining. The incoming air was passed through two cloth tubes which diffused it over the face. Air left through a single opening at the rear of the helmet. The temperature of the incoming and outgoing air was measured.

4. Insulative Clothing. In some experiments, only an intermediate weight flying suit (A-11A trousers, B-15 jacket) of 2.1 clo was worn over the barrier coverall. However, in most of the experiments the insulation of the outer clothing was increased to 2.5 clo by the addition of a light, one piece, flying suit. An anti-exposure suit was worn in preliminary experiments. It was discarded because an impermeable outer garment imposes no additional stress when sweat can be evaporated. The hands and feet were excluded from the ventilating air by the tight wristlets and anklets of the barrier coverall. Type F-3 gloves provided the equivalent of 1.0 clo insulation for the hands. The feet were insulated with woolen socks, felt inserts, and heavy boots; the total insulation of this assembly, expressed in clo, was 2.6.

B. Measurements and Calculations

1. General. Measurements were made to determine the rate of change of heat content of the ventilating air, to determine the steady state heat surplus and to detect physiological strain. The head presented a special problem. The shape and fit of the helmet, the ability of the air to circulate freely over the face and ears, the necessity for removal of exhaled water vapor, and the oxygen requirements are primary considerations in determining helmet ventilation. Thus, it was impossible to delineate general requirements for the head related only to the ambient temperature, activity of the subject, and amount of insulation over the circulating air. For this reason, the head was considered apart from the rest of the body, and a detailed analysis was made of the requirements

for the body with the head excluded.* The requirements for head ventilation are presented separately and are for a loose fitting helmet with an air space permitting circulation of ventilating air about the head. They may not apply to other types of helmet.

2. The Change of Heat Content of the Ventilating Air. The rate of change of heat content of the ventilating air was determined separately for each body region, and these values (excluding the head) were added to give the rate of change in heat content of the ventilating air for the "body", $\Delta H_v'/t$. Flow rate, inlet and outlet air temperatures were obtained for each region as described above.

3. The Steady State Heat Surplus. The steady state heat surplus of the "body" is defined as the difference between the rates of sensible heat production and of heat leakage through the clothing.

To determine the sensible heat production rate of the "body", Q_b'/t , the sensible heat production of the entire man was found by subtracting the evaporative heat loss from the total metabolic heat production. Since the area of the head is approximately 8% of the body area, 8% of the sensible heat production for the entire man was subtracted from that value to give the sensible heat production for the "body", i.e.,

$$Q_b'/t = (Q_m/t - Q_e/t) - 0.08(Q_m/t - Q_e/t) \quad (7)$$

The heat lost by warming the inspired air was negligible (0.5 - 2.0 Cal./hr.) within the range of inlet air temperatures used. The subject remained seated and quiet during the experimental period. In the first six experiments, metabolic rate was measured by oxygen consumption in the post-absorptive period. It was found to vary between 43 and 57 Cal./sq.m./hr. Measurement of metabolic rate was then discontinued and an average value of 50 Cal./sq.m./hr. was assumed for the later experiments. In the majority of experiments at room temperature or above, evaporative heat loss was determined by weighing the dressed subject before, during and after the experimental period. In the experiments at low ambient temperatures, evaporative heat loss was taken to be 40% of the metabolic heat production, the average of the determinations. This figure corresponds to that given in the Heating Ventilating Air Conditioning Guide (12) as the evaporative heat loss of a sitting, resting man at 79° F.

The heat leakage rate through each region of the clothing was calculated separately and weighted according to the area of the region; these (except for the head) were added to give the total heat leakage

*The body minus the head will be written, "body".

rate through the "body" clothing, Q_g'/t . Heat exchanges were calculated from copper man measurements of insulation, and from regional averages of the differences between operative temperatures and barrier coverall temperatures for the ventilated regions; or between operative temperatures and skin temperatures for the non-ventilated areas. Average, regional coverall temperatures were taken from thermocouples connected in parallel: four on each limb and twelve over the trunk. The location of hand and foot thermocouples is given in Table 1. The area of the barrier coverall, 2.33 sq.m., and of each of its regions was measured on the patterns. Air Force Man (14) hand and foot areas, 0.11 and 0.16 sq.m. respectively, were assumed for the calculations.

4. Detection of Physiological Strain. Physiological strain was evaluated by determining the rate of change in stored body heat; by measuring the rate of sweating in experiments above room temperature; by following the temperature of the non-heated hands and feet in experiments in the cold; and by subjective comments.

Change in stored body heat was calculated from the equation:

$$\Delta H_b = (W_b) C_b (\Delta T_b) \quad (8)$$

Where:

ΔH_b is the change in stored body heat.

W_b is the body weight in Kg.

C_b is the specific heat of the body = 0.83 Cal./Kg./°C. (13)

ΔT_b is the change in average body temperature in °C.

Skin and rectal temperatures were measured at 30 minute intervals. The difference between the 30 minute average body temperature determination and the final determination was taken as ΔT_b . The first 30 minutes of the experimental period were excluded to minimize temperature changes resulting from the evaporation of sweat accumulated during dressing. The rate of change of stored heat was expressed as Cal./hr. Average body temperature was calculated by weighting the rectal temperature 67% and the average skin temperature 33%.

To calculate average skin temperature, the body surface was divided into six areas: head, trunk, arms, hands, legs, and feet. The averages for these areas were determined from skin temperatures measured at the locations listed in Table 1. Each was assigned a weighting coefficient according to its surface area, and the six weighted average regional skin temperatures were summed to give the average skin temperature.

TABLE 1

Body Area	Weighting Coefficient	No. of Thermocouples	Location of Thermocouples
Head*	0.078	2	Forehead, right mastoid process.
Trunk	0.282	5	Scapula, nipple, abdomen, kidney, right rump.
Arms	0.150	2	Left upper arm, lower right arm.
Legs	0.347	5	Right thigh, left thigh, right knee, left knee, left calf.
Hands	0.060	5	Right thumb, third and fifth fingers, palm, and back, and connected in parallel to give an average hand temperature.
Feet	0.085	6	Left foot, on ball of great toe, heel, dorsum at bases of first and fifth toes, and below the medial and lateral malleoli, and connected in parallel to give an average foot temperature.

* In some experiments the thermocouples for the head were used on the left third finger and the right great toe. When this was done an average head temperature of 90° F. was assumed.

5. A Sample Calculation follows:

Conditions.

Operative temperature = +120° F.

Inlet air temperature = 77° F. ±1° F.

Air Flow:

Area	CFM	Lbs./min.
Trunk	12.8	0.96
Arms	7.7(x2)	0.58(x2)
Legs	13.3(x2)	1.00(x2)
"Body"	54.8	4.12
Helmet	2.5	0.19

Calculation of $\Delta H_v'/t$.

The rate of change in heat content of the ventilating air is calculated separately for each area and summed to give the change in heat content of the ventilating air for the "body".

$$\Delta H_v^r/t = (W_v^r/t) C_v (T_{v2}^r - T_{v1}^r)$$

$$\Delta H_v'/t = \sum \Delta H_v^r/t$$

Superscript r is used to denote any given region. C_v is 0.24 cal./gm./°C. for dry air. It is included in a constant, k_v , which converts the grams into pounds, °C. into °F., small calories into large calories, and minutes into hours:

$$k_v = \frac{(454 \text{ gm}) (60 \text{ min.}) (0.24 \text{ cal./gm./°C.})}{1000 \times 1.8} = 3.63$$

Area	$(T_{v2}^r - T_{v1}^r)$ (°F.)	W_v^r/t (lbs./min.)	$\Delta H_v^r/t$ (Cal./hr.)
Trunk	9.1	0.96	32.0
Rt. Leg	8.7	1.00	31.5
Lft. Leg	8.3	1.00	30.0
Rt. Arm	8.3	0.58	17.5
Lft. Arm	9.4	0.58	19.5

$$\Delta H_v'/t = 130.5; \text{ i.e., } 131$$

Calculation of Q_g'/t .

The heat leakage rates are calculated separately for each region, and added to give the total heat leakage through the "body" clothing.

$$Q_g^r/t = \frac{3.09 (T_c^r - T_o) (A_c^r/A_c)}{I_g^r + I_a}$$

$$Q_g'/t = \sum Q_g^r/t$$

The factor A_c^r/A_c (the surface area of the region of the barrier coverall in question divided by the total area of the coverall) weights the heat exchange through the region according to its area. For the hands and feet, the

average skin temperature of the part is substituted for a coverall temperature, and the area of the hand or foot (A_s^r) for the weighting factor (A_c^r/A_c).

Area	$(T_c^r - T_o)$ (°F.)	$I_g^r + I_a$ (clo)	A_c^r/A_c	Q_g^r/t (Cal./hr.)
Trunk	-34.5	3.3	0.951	-30.0
Rt. Leg	-32.5	3.3	0.448	-13.5
Lft. Leg	-32.5	3.3	0.448	-13.5
Rt. Arm	-32.5	3.3	0.246	- 7.5
Lft. Arm	-32.0	3.3	0.246	- 7.5
	$(T_s^r - T_o)$		A_s^r	
Hands	-21.5	1.8	0.11	- 4.0
Feet	-23.5	3.4	0.16	- 3.5

$$Q_g'/t = -79.5, \text{ i.e., } -80$$

Calculation of $Q_b't$.

Area of subject 1.9 sq. m.

Metabolic heat production = (50 Cal./sq.m./hr.) (1.90 sq.m.)
= 95 Cal./hr.)

Weight loss = 76.5 gm./hr.

Evaporative heat loss (Q_e/t) = (76.5 gm./hr.) (0.58 Cal.)
= 44 Cal./hr.

Sensible heat production of whole body = 95 Cal./hr.
-44 Cal./hr.
= 51 Cal./hr.

Sensible heat production of the "body" = 51 Cal./hr.
-8% (51 Cal./hr.)
= 47 Cal./hr.

Calculation of Q_{σ}'/t .

$$\begin{aligned} Q_{\sigma}'/t &= Q_b'/t - Q_g'/t \\ &= 47 \text{ Cal./hr.} - (-80 \text{ Cal./hr.}) \\ &= 127 \text{ Cal./hr.} \end{aligned}$$

IV. RESULTS

A. General

The data are presented in Tables 2 through 7. Some results upon the temperature regulation of the extremities are reserved for Section VI. Experiments labelled A and B were performed consecutively during the same day upon the same subject. Any assumed values are starred (*). The rate of change in heat content of the air that ventilates the "body" ($\Delta H_v'/t$) and the rate of heat leakage through the "body" clothing (Q_g'/t) are given with the measurements necessary for their calculation. Ventilating air temperatures (T_{v1} , T_{v2}) are averages of the regional ventilating air temperatures (excluding the head) weighted by the amount of air supplied each region. The average barrier coverall temperature (T_c) is the sum of the regional barrier coverall temperatures weighted according to the area of the regions. The rate of sensible heat production of the "body" (Q_b'/t) is determined as illustrated above. Evaporative heat loss rate (Q_e/t), rate of change of stored body heat ($\Delta H_b/t$), skin, rectal and average body temperatures at 30 minute intervals, and subjective reactions are given to indicate physiological strain. All values are in terms of "body" area rather than per square meter. This was 1.75 sq.m. for all subjects except E.P., for whom it was 1.63 sq.m.

The error in the determination of $\Delta H_v'/t$ may be estimated as $\pm 5\%$. The accuracy in reading the rotameters was 2-3 liters/min. The inlet air temperatures were measured about 5 inches from the actual entrance of the air beneath the outer clothing; although the inlet tubes were well insulated, a small, unknown amount of heat was undoubtedly lost in this distance. On two or three occasions there was a variation of as much as 10° F. in the outlet air temperatures obtained from different body regions receiving the same amount of air. The reason for this is unknown, but it may be postural.

The error in the determination of Q_g'/t was also probably about $\pm 5\%$, but possibly could have been as great as $\pm 10\%$. Its main source, as noted earlier, is the addition of I_a to I_g to determine the total insulation. There is also a small error in I_g arising from differences in fit of the clothing upon the subjects, and between the subject and the copper man upon which the insulation was originally measured. Another source of error is the assumption that the heat transfer surface of the barrier coverall equalled its measured area (2.33 sq.m.).

B. The Experiments at 180° F. - Table 2.

There was remarkably little evidence of thermal dis-equilibrium over the wide range of ventilating air flows and temperatures used. In Experiments 9-15B, 9-23B, 9-24A, 9-26A, 9-26B, 10-1A, 10-1B, $\Delta H_v'/t$ varied from 251 to 334 Cal./hr. (average, 297 Cal./hr.), yet there was no indication of physiological strain. The temperature range of the ventilating air was 46-48° F. to 66-68° F. In Experiments 9-15A and 9-23B, $\Delta H_v'/t$ was purposely kept low (215 Cal./hr and 204 Cal./hr., respectively); the subject, although warm, was not uncomfortable. The $\Delta H_b/t$ was +22 Cal./hr. in the former experiment. In the latter it was +6 Cal./hr., but the rate of evaporative heat loss was 60 Cal./hr. In Experiment 9-23A, $\Delta H_v'/t$ equalled 355 Cal./hr.; the subject complained of chilliness throughout the experiment, and $\Delta H_b/t$ was -16 Cal./hr. Some chilliness was noticed at the start of each experiment due to the evaporation of sweat accumulated during dressing. Because, in several experiments, not enough weighings were made to eliminate this loss of accumulated sweat in the determination of Q_e/t , an assumed value (40% of the metabolic heat production) was taken in Experiments 9-23A, 9-24A and 9-26A. No such value could be assumed for Q_e/t in Experiment 9-15A since the subject was warm and storing heat. The reason for the low T_{v2} and, consequently, the low $\Delta H_v'/t$ in Experiment 10-1B (as compared to Experiments 9-15B and 9-26A) is unknown.

There was considerable sweating of the non-ventilated hands and feet but these parts were otherwise comfortable, provided their circulation was not restricted. However, average hand temperature usually rose to 105-106° F., and average foot temperature to 101-104° F. The highest average hand and foot temperatures recorded were 109.0 and 107.5° F., respectively. One subject received several small second degree burns on the finger tips where tape, to fasten thermocouples, had been applied too tightly. It was apparent that the hands would need more protection, probably by inclusion within the ventilating circuit, if metal were to be handled for any length of time at 180° F.

C. The Experiments at +120° F. - Table 3.

It was not difficult to prevent warming at 120° F. In experiments 10-7A, 10-8A, 10-13 and 10-23A, the subject remained completely comfortable; $\Delta H_v'/t$ varied between 123 and 138 Cal./hr. (average of 131 Cal./hr.). Use of 4.1 lbs./min. of 76-78° F. ventilating air or 2.5 lbs./min. of 66-68° F. air proved equally satisfactory. In Experiments 10-2B and 10-7B slight chilliness was noticed; $\Delta H_v'/t$ was 133 and 157 Cal./hr., respectively, although 1.8-1.9 lbs./min. of 58-59° F. ventilating air was used in each. In Experiment 10-2A the subject complained of moderate chilliness. The $\Delta H_v'/t$ was 150 Cal./hr. (3.3 lbs./min. of 67-68° F. ventilating air). The subject was somewhat warm during Experiment 10-8B, in which $\Delta H_v'/t$ was 102 Cal./hr., and uncomfortably warm in Experiment 10-23B, for which $\Delta H_v'/t$ was reduced to 87 Cal./hr.

There was some discrepancy between the subjective response and $\Delta H_b/t$. The subject was comfortable during Experiment 10-7A but $\Delta H_b/t$ equalled -19 Cal./hr.; yet in Experiment 10-2A the subject felt chilly and $\Delta H_b/t$ was only -8 Cal./hr. In Experiment 10-23B the subject was uncomfortably warm but $\Delta H_b/t$ was only +10 Cal./hr. However, Q_e/t was increased to 73 Cal./hr. During Experiment 10-8B there was no objective evidence of strain although $\Delta H_v'/t$ was low and the subject felt too warm.

D. The Experiments at Room Temperature - Table 4.

Ambient temperature varied from 72 to 81° F. In this range, T_c is greater than T_o and heat moves outwards through the clothing. However, even with light clothing, the rate of heat loss is less than the rate of sensible heat production of the sitting resting subject. The ventilating air, to maintain thermal equilibrium, must remove that fraction of the sensible heat not lost through the clothing, and evaporate the insensible perspiration. The experiments reveal that this can be done with a very small amount of room temperature ventilating air.

The total insulation over the ventilating air in the first three experiments was 3.5 clo; in later experiments it was reduced to 2.9 clo. This resulted in very little change in the rate of heat leakage through the clothing because the difference between T_c and T_o is small at room temperature. In those experiments in which the subject was comfortable, the $\Delta H_v'/t$ varied between 23 and 29 Cal./hr. Use of 0.8 lbs./min. of 72-75° F. ventilating air or 0.4 lbs./min. of 64-67° F. air proved equally satisfactory. The use of larger amounts (1.6 lbs./min.) of ventilating air at a temperature a little below skin temperature (87-88° F.) was unsatisfactory-- $\Delta H_v'/t$ was only 3-6 Cal./hr. (Exps. 5-15 and 5-28). The subjects were somewhat warm and noticed slight sweating, but $\Delta H_b/t$ did not exceed +10 Cal./hr. It is to be emphasized that an increase in temperature of the ventilating air, while precluding an appreciable change in its heat content, does not appreciably affect the evaporation of sweat.

E. The Experiments at 0° F. - Table 5.

The temperature of the extremities must be sustained to maintain comfort in the cold. The quantity of heat needed to do this will depend upon whether or not artificial heat is directly applied to these parts. The problem is discussed in detail in Section VI. It is enough to state here that if artificial heat is supplied to the hands and feet, the quantity of heat furnished to other areas may be reduced to that necessary to slow the rate of fall of deep body temperature, over the period of the exposure, so that a total of not more than about 50 Calories is lost. If, as in these experiments, they receive no artificial heat, a greater amount of heat must be supplied to the rest of the system, i.e., enough heat must be supplied to prevent vasoconstriction in the extremities and allow an adequate circulatory supply of heat to these parts.

TABLE 2
180°F. EXPERIMENT

Exp. No.	9-15A	9-15B	9-23A	9-23B	9-23A	9-23B	9-26A	9-26B	10-1A	10-1B
Subject	S.R.	S.R.	H.S.	H.S.	H.S.	H.S.	S.R.	S.R.	H.S.	H.S.
T ₀	181.0	181.5	179.5	179.0	177.5	161.5	186.0	186.0	180.0	181.5
I	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
lts/min	2.5	4.3	4.0	3.2	6.5	2.6	4.1	3.3	3.3	4.0
T _{v1}	62.5	60.0	47.5	48.5	67.5	67.5	58.0	47.5	48.0	57.0
°F.	68.5	80.5	72.0	75.5	83.5	90.5	80.5	76.5	72.5	75.0
T _{v2}	21.5	30.6	355	310	251	204	320	334	290	265
Gal/hr										
Δt ₁₆ /t										
°F.	91.0	87.5	83.0	85.0	89.0	93.0	85.0	86.0	82.0	84.0
Cal/hr	-221	-227	-239	-233	-219	-220	-253	-246	-241	-243
T _g /t										
Cal/hr	--	52	52	53	48	26	52	53	54	70
T ₀ /t	--	38	68	37	35*	60	38*	37	36	19
Δt ₁₆ /t	22	-6	-1.0	9	4	6	5	3	-1.0	0
Temp.	T ₀	T ₀	T ₀	T ₀	T ₀	T ₀	T ₀	T ₀	T ₀	T ₀
Control	91.9	96.6	92.2	96.9	92.3	92.3	99.8	89.7	92.6	89.6
C	96.7	95.0	96.0	95.0	96.9	95.8	95.1	95.0	95.6	95.9
30	91.1	99.2	96.6	98.1	90.9	99.0	99.0	98.0	98.0	98.0
60	91.8	99.4	96.3	98.9	91.3	99.1	99.1	98.0	98.1	98.4
90	91.5	100.2	96.9	99.0	91.0	99.2	99.2	99.0	98.4	98.9
120										
150										
160										
Comment	Harm	Comfortable	Millineas	Comfortable except for slight chilliness	Comfortable	Warm but bearable	Comfortable	Comfortable except for slight chilliness	Comfortable	Comfortable

TABLE 3
120°F. EXPERIMENTS

Exp. No.	10-2A	10-2B	10-7A	10-7B	10-8A	10-8B	10-13	10-23A	10-23B
Subject	E.P.	E.P.	H.S.	H.S.	S.P.	S.R.	H.S.	H.S.	H.S.
Op.	117.5	123.0	123.0	120.0	118.5	121.0	121.0	119.0	122.0
clo	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3	3.3
lbs/min	3.3	1.9	2.5	1.8	4.1	4.1	4.1	4.1	2.1
T _{sk} /t	67.5	58.0	67.0	57.0	76.0	83.5	77.0	77.5	65.5
T _{re} /t	81.0	77.5	82.5	79.5	83.0	90.5	85.5	86.5	84.0
ΔH _{sk} /t	130	133	138	157	122	102	131	133	87
Op.	83.5	83.5	84.5	84.0	86.5	93.0	88.0	89.0	90.5
T _{sk} /t	-83	-94	-91	-89	-79	-71	-80	-71	-74
T _{re} /t	48	53	53	65	56	70	47	50	20
T _{sk} /t	35*	29	37	24	34	19	44	41	73
ΔH _{sk} /t	-8	-16	-19	—	-3	-4	+5	+4	+10
Temp.	T _{sk}	T _{sk}	T _{sk}	T _{sk}	T _{sk}	T _{sk}	T _{sk}	T _{sk}	T _{sk}
Control	95.4	95.4	95.4	95.4	95.4	95.4	95.4	95.4	95.4
0	85.1	85.1	85.1	85.1	85.1	85.1	85.1	85.1	85.1
30	86.3	86.3	86.3	86.3	86.3	86.3	86.3	86.3	86.3
60	87.2	87.2	87.2	87.2	87.2	87.2	87.2	87.2	87.2
90	87.7	87.7	87.7	87.7	87.7	87.7	87.7	87.7	87.7
120	87.9	87.9	87.9	87.9	87.9	87.9	87.9	87.9	87.9
150	87.3	87.3	87.3	87.3	87.3	87.3	87.3	87.3	87.3
160	87.3	87.3	87.3	87.3	87.3	87.3	87.3	87.3	87.3
Comment	milky	Slightly milky	Comfortable	Slight chilliness first part	Comfortable	Comfortable some sweating	Comfortable	Comfortable	Uncomfortable profuse sweating

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9 2000

Exp. No.	4-21	4-29	5-6	5-14	5-15	5-28	6-3	6-4
Sub Jet								
T _o	O.H. 74.5	R.D. 71.0	S.R. 72.0	R.D. 75.0	S.R. 81.0	R.D. 78.5	S.R. 78.5	O.H. 78.5
clo	3.5	3.5	3.5	2.9	2.9	2.9	2.9	2.9
W _o /t	0.8	0.7	0.8	0.8	1.6	1.6	0.4	0.4
W _o /min	75.5	72.0	74.0	74.0	87.5	87.0	67.0	64.0
T _o	84.5	82.5	83.5	82.0	88.5	87.0	83.5	80.5
ΔT _o /t	25	29	27	23	6	3	23	24
ΔT _o /hr.								
T _c /t	89.5	88.0	87.5	86.5	90.5	89.5	85.0	86.5
Q _o /hr.	39	39	40	35	29	32	35	40
Q _o /hr.	56	57	64	52	51	55	66	70
Q _o /hr.	37	32	38	27	34	35	23	19
ΔH _o /t	-4	-3	-4	42	48	49	42	37
Temp. Control								
0	T _o 99.0	T _o 98.3	T _o 99.3	T _o 97.8	T _o 89.7	T _o 89.6	T _o 88.5	T _o 99.1
0	T _o 92.9	T _o 91.5	T _o 90.4	T _o 90.7	T _o 95.3	T _o 95.9	T _o 95.8	T _o 95.5
0	T _o 92.1	T _o 91.9	T _o 91.2	T _o 91.3	T _o 90.9	T _o 90.5	T _o 90.5	T _o 95.4
30	T _o 92.1	T _o 91.9	T _o 91.2	T _o 91.3	T _o 90.9	T _o 90.5	T _o 90.5	T _o 95.4
60	T _o 92.9	T _o 91.7	T _o 91.0	T _o 91.3	T _o 90.9	T _o 90.5	T _o 90.5	T _o 95.4
90	T _o 92.9	T _o 91.7	T _o 91.0	T _o 91.3	T _o 90.9	T _o 90.5	T _o 90.5	T _o 95.4
120	T _o 92.3	T _o 91.7	T _o 91.0	T _o 91.3	T _o 90.9	T _o 90.5	T _o 90.5	T _o 95.4
150	T _o 92.3	T _o 91.7	T _o 91.0	T _o 91.3	T _o 90.9	T _o 90.5	T _o 90.5	T _o 95.4
180	T _o 92.3	T _o 91.7	T _o 91.0	T _o 91.3	T _o 90.9	T _o 90.5	T _o 90.5	T _o 95.4
Comment	Comfortable, slight sweating over back	Comfortable	Comfortable	Comfortable	Slight sweating	Drowsy, slight sweating	Comfortable	Gaily first few minutes, then comfortable

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Exp. No.	7-15	7-29A	7-29B	7-31	8-5A	8-7A	8-7B	10-21	
Subject	R.D.	S.R.	S.R.	R.P.	S.R.	R.D.	R.D.	S.R.	
T _a	-1.0	41.0	40.5	43.5	42.0	43.0	42.0	44.0	
T _c	2.6		2.6	2.6	2.8	2.8	2.8	3.2	
T _w /min	2.4	1.8	2.4	2.6	2.5	4.1	2.5	2.5	
T _{sk} /°C	8.0	117.5	113.5	117.5	121.0	111.0	110.0	118.5	
T _{re} /°C	75.0	90.5	95.0	98.0	94.5	97.5	92.0	97.5	
Δt _{sk} /°C	-105	-174	-162	-234	-237	-205	-169	-189	
CAL/hr									
T _e /°C	76.0	88.5	93.5	96.0	90.5	90.5	86.5	93.5	
Q _e /kcal/hr	285	254	260	277	265	261	250	231	
CAL/hr	52	52	52	48	52	52	52	52	
Q _{sk} /kcal/hr	36	36	36	35	36	36	36	36	
Δt _{sk} /°C	-27	—	+30	-3	0	0	-4	+34	
Temp. Control	T _a 91.5 87.2 86.5 84.1	T _a 90.5 89.3 88.7 86.5	T _a 90.5 89.8 89.0 88.5	T _a 91.6 91.9 92.1 90.5	T _a 92.6 93.1 93.1 92.0	T _a 93.1 93.6 93.6 92.6	T _a 93.1 93.6 93.6 92.6	T _a 93.1 93.6 93.6 92.6	T _a 96.2 96.5 97.0 96.9
0	91.5	92.0	92.2	92.2	92.2	92.2	92.2	92.2	
30	92.2	92.2	92.2	92.2	92.2	92.2	92.2	92.2	
60	92.9	92.9	92.9	92.9	92.9	92.9	92.9	92.9	
90	92.8	92.8	92.8	92.8	92.8	92.8	92.8	92.8	
120	92.8	92.8	92.8	92.8	92.8	92.8	92.8	92.8	
150	92.8	92.8	92.8	92.8	92.8	92.8	92.8	92.8	
180	92.8	92.8	92.8	92.8	92.8	92.8	92.8	92.8	
Percent entire body in 3 minutes	100	100	100	100	100	100	100	100	
Body, hands and feet comfortable	Body, hands & feet comfortable	Hands required electrical heating, feet cold, body comfortable	Body, hands & feet comfortable	Body, hands & feet comfortable	Body, hands and feet comfortable	Body, hands and feet comfortable	Body, hands and feet comfortable	Body, hands and feet comfortable	

4900-M-AML

-20° F. EXPERIMENTS

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TABLE 7

-30°F. EXPERIMENTS

Exp. No.	9-9	9-10	9-17	11-4
Subject	E.P.	H.S.	S.R.	E.P.
T _o	-30.5	-31.0	-31.0	-31.0
I	3.2	3.2	3.2	3.2
W _v /t	4.2	4.2	4.2	4.8
T _{v1}	120.0	120.0	119.5	118.5
T _{v2}	101.0	100.5	98.5	103.0
ΔH _v /t	-287	-289	-301	-265
T _c	95.5	94.5	95.5	94.0
Q _g '/t	327	322	320	323
Q _o '/t	48	52	52	48
Q _e '*/t	35	38	38	35
ΔH _b /t	+3	-3	+11	-11
Temp.				
C				
0	T _s 92.9	T _s 93.8	T _s 91.6	T _s 94.1
30	92.4	92.8	93.5	90.3
60	96.8	96.0	94.7	98.4
90	97.4	95.6	95.7	98.3
120	96.5	96.7	97.0	97.1
150	97.0	97.2	96.5	95.7
180	97.3	97.4	96.1	97.4
	T _r 98.9	T _r 99.4	T _r 99.0	T _r 99.8
	99.4	99.8	99.5	99.8
	99.0	99.0	99.4	99.8
	99.0	98.2	99.8	99.8
	98.7	98.3	99.9	99.8
	98.5	98.5	99.8	99.8
	98.5	98.1	98.7	98.9
	99.4	98.6	98.6	98.5
	T _b 97.0	T _b 97.6	T _b 96.5	T _b 98.3
	97.1	97.5	97.6	96.7
	98.2	98.0	97.9	99.4
	98.4	97.4	98.5	99.3
	97.9	97.8	98.9	98.9
	98.0	98.1	98.7	98.5
	98.1	97.8	98.6	98.7
	98.6			
Comment	Body, hands and feet comfortable	Body, hands and feet comfortable	Body, hands and feet comfortable	Body, hands and feet comfortable

Experiments 7-31, 8-5A, 8-7A reveal that when the total insulation over the ventilating air was 2.8 clo (and of the hands and feet, 1.7 and 3.3 clo, respectively) deep body and extremity temperatures were maintained with $\Delta H_v'/t$ between -205 and -237 Cal./hr. (average of -225 Cal./hr.). When the total insulation over the air was increased to 3.2 clo (Exp. 10-21) $\Delta H_v'/t$ of -189 Cal./hr. sufficed for comfort ($\Delta H_b/t = +14$ Cal./hr.). In Experiments 7-15 and 7-29A, $\Delta H_v'/t$ was -105 and -174 Cal./hr., respectively (considerably below that later found necessary); as expected, the hands and feet cooled rapidly and the hands were painful within 60 minutes.

A $\Delta H_v'/t$ sufficient for comfort was obtained from 2.3-2.6 lbs./min. of 118-120° F. air, or 4.1 lbs./min. of air at 111° F. Air warmer than 120° F. could not be used because of the danger of burning the skin. Air cooler than 110° F. was not feasible because of the large quantity which would have to be circulated beneath the clothing.

F. The Experiments at -20° F. - Table 6.

Deep body and extremity temperatures were maintained in two experiments (Exps. 8-14, 8-25) in which $\Delta H_v'/t$ was -293 and -307 Cal./hr., respectively; and the total insulation over the ventilating air was 2.8 clo. This required 4.0-4.1 lbs./min. of 119-120° F. ventilating air. In two other experiments the total insulation over the air was increased to 3.2 clo (Exps. 8-27A, 8-27B). The added protection was overestimated, and the amount of air used was too small. In Experiment 8-27A, $\Delta H_v'/t$ was only -199 Cal./hr. and the hands were painful within 30 minutes. When $\Delta H_v'/t$ was increased to -230 Cal./hr. (8-27B) the hands rewarmed and the temperature of the feet was sustained at about 70° F.

G. The Experiments at -30° F. - Table 7.

Internal body and extremity temperatures were maintained in all four experiments presented in this table; $\Delta H_v'/t$ varied from -265 to -301 Cal./hr. (average 286 Cal./hr.). This was accomplished with 4.2-4.8 lbs./min. of 118-120° F. ventilating air. Other experiments at -30° F., designed to study the temperature response of the extremities in greater detail, are presented in Section VI.

H. The Requirements for Helmet Ventilation.

At 0, -20 and -30° F., the supply of 0.19 lbs./min. of 85-100° F. ventilating air to the helmet sufficed for comfort. There was no subjective difference between air at 85 and 100° F. At 120° F. comfort was sustained by 0.19 lbs. of 75-88° F. ventilating air. At 180° F. the flow rate had to be increased to 0.37 lbs./min., and in one subject to 0.57 lbs./min.; the temperature range of the ventilating air was 60-72° F. Use of less air resulted in an unpleasant feeling of warmth over the face, and burning of the eyes.

As noted above, the ventilating requirements largely depend upon the design of the helmet. That relatively small amounts of air sufficed in these experiments is related to the fact that the helmet fitted loosely, and was separated from the head by an air space. Heat leakage through the helmet was about -30 Cal./hr. at -30° F., and about +30 Cal./hr. at 180° F.

V. DISCUSSION

A. The Criteria for "Thermal Balance".

Since indications of physiological strain in the cold and at high ambient temperatures are different, the criteria used to determine "thermal balance" varied with the ambient temperature. At 180 and 120° F. they were:

- 1) That the change of heat content of the ventilating air ($\Delta H_v'/t$) and the steady state heat surplus ($Q\sigma'/t$) be within about 10% of each other.
- 2) A relatively constant rectal temperature with a difference of no more than 0.7° F. between the thirty minute and final readings.
- 3) An evaporative heat loss of less than 45 Cal./hr.
- 4) The absence of discomfort.

At room temperature, since $Q\sigma'/t$ was only 20-25 Cal./hr., the only criteria used for "balance" were change of rectal temperature of less than 0.7° F., and absence of discomfort. The only experiments not considered "balanced" were Experiments 5-28 and 6-3 ($\Delta H_v'/t$ of 6 and 3 Cal./hr., respectively).

At low ambient temperatures, the maintenance of the average temperature of the non-ventilated hands and feet above 70° F. was taken as indication that the body was receiving sufficient heat. Slightly more heat than was calculated to be necessary was usually supplied to the system on the assumption that vasoconstriction in the non-ventilated extremities would be less apt to occur if the body were slightly overheated. Therefore, $\Delta H_v'/t$ exceeded $Q\sigma'/t$ by 5-20% in experiments that were called "balanced". However, in no instance did rectal temperature increase over 0.7° F. from the thirty minute reading. Whether or not evaporative heat loss was increased was not measured, but no active sweating was noticed. At no time did the subject feel too warm. (However, this may have been due to the fact that the subject expected, if anything, to feel cold. It is possible that the same degree of overheating at 180° F. would have resulted in discomfort.)

Rectal temperature was used as a criterion of "balance" in place of $\Delta H_p/t$, because the validity of skin temperatures for the calculation of average body temperature is dubious when there are large differences between adjacent regions. There was often 10-15° F. difference between temperature readings from a skin area near an inlet air opening and a nearby compression area. This obscured the meaning of the absolute value obtained for a single skin temperature reading. Also, since no method was readily available to determine the air flow patterns, the calculation of the average regional skin temperature was subject to a considerable error. The best compromise was to place the skin thermocouples so as to include areas near the harness openings and compression areas, if they made up a sizeable part of the region. For example, in placing one of the five trunk thermocouples on the scapula and another on the rump, the compression areas of the trunk were taken to be two fifths of the total trunk area.

B. Reduction of Data to a Standard.

1. Reduction to Standard Area. In order that data may be compared, it is desirable to reduce them to a standard area. That of the Air Force man (1.84 sq. m.) has been chosen (14). A corrected steady state heat surplus for the Air Force man "body", Q_b'/t (Section III-B) may be calculated from the experimental data by the following equation:

$$Q_b'/t = (Q_p'/t) (1.69/A'_s) - (Q_g''/t) (2.26/A_c) + (Q_{n+f}/t) \quad (9)$$

Where:

1.69 is the "body" area of the Air Force man.

A'_s is the "body" area of the experimental subject.

Q_g'' is the sum of the heat leakages only through the regions covered by the barrier coverall.

2.26 is the heat transfer surface of the barrier coverall for the Air Force man. This was assumed to be the product of 2.33 (the measured barrier coverall area) and the ratio of the "body" surface area of a 1.90 sq.m. man to the Air Force man's "body" area. And,

Q_{n+f} is the sum of the heat leakage through the gloves and footgear.

The reasons for correcting the rate of heat leakage through the "body" clothing (Q_g'/t) by breaking it down into Q_g''/t and Q_{n+f} are:

1) The average temperature of the barrier coverall, and therefore the heat leakage through it, will vary with the flow and temperature

of the ventilating air. However, the heat leakage through the non-ventilated gloves and footgear is dependent upon the average skin temperature of the hands and feet; which, in turn, is determined primarily by the thermal state of the body.

2) It is important to know the variation of Q_g'/t with different amounts of clothing worn over the coverall. Variation of insulation over the coverall is independent of change of insulation of gloves and footgear.

3) The effective heat transfer area of the barrier coverall may change appreciably with subjects of different area, while the area of the hands and feet, because it is small, may be considered to remain essentially the same. (The values for the Air Force man, 0.11 sq. m. for the hands and 0.16 sq.m. for the feet, were used throughout.) A corrected $\Delta H_v'/t$ was taken as the product of the experimental $\Delta H_v'/t$ and the ratio of the "body" area of the experimental subject to that of the Air Force man. Values for Q_b'/t , Q_g''/t , Q_{h+f} , Q_{σ}'/t , and $\Delta H_v'/t$ reduced to Air Force man area are given in Table 8.

2. The Standard Steady State Heat Surplus. Different values for Q_{σ}'/t for the same environmental conditions may be found in Table 8. This is the result of the variation in barrier coverall temperatures with variation in the difference between $\Delta H_v'/t$ and Q_{σ}'/t ; and to increased evaporative heat loss when the subject was overheated. In those experiments above room temperature in which $\Delta H_v'/t$ exceeded Q_{σ}'/t , barrier coverall temperatures rose. The reverse was true at low ambient temperatures. Therefore, to predict ventilating air requirements, a standard steady state heat surplus, Q_{σ}'/t , had to be determined, which would vary only with operative temperature, insulation over the ventilating air, and activity of the subject. The equation for this standard value may be written most simply as:

$$\bar{Q}_{\sigma}'/t = \bar{Q}_b'/t - \bar{Q}_g'/t \quad (10)$$

Where:

\bar{Q}_b' is the standard sensible heat production of the "body".

\bar{Q}_g' is the standard rate of heat leakage through the "body" clothing.

To determine \bar{Q}_b'/t , values for metabolic heat production at various activities may be obtained from the Heating Ventilating Air Conditioning Guide (12). The standard evaporative heat loss, Q_e/t , has been taken as 40% of \bar{Q}_m/t . The correction for exclusion of the head must be made as described in Section III-B. The equation is:

TABLE 8
HEAT VALUES REDUCED TO AIR FORCE MAN

Exp. No.	T ₀	I.	Q _b '/t	Q _g "/t	Q _{n+f} /t	Q _o '/t	ΔH _v '/t
	°F.	clo	Cal/hr.	Cal/hr.	Cal/hr.	Cal/hr.	Cal/hr.
9-15A	184	3.3	—	-189	-25	—	209
9-15B	184	3.3	51	-196	-25	274	297
9-23A	180	3.3	51	-207	-26	286	345
9-23B	179	3.3	51	-202	-26	279	301
9-24A	178	3.3	51	-188	-25	266	261
9-24B	182	3.3	29	-188	-26	243	204
9-26A	186	3.3	51	-218	-28	299	311
9-26B	186	3.3	51	-215	-27	293	324
10-1A	180	3.3	52	-209	-26	287	282
10-1B	180	3.3	67	-211	-26	304	257
10-2A	118	3.3	52	-74	-7	133	156
10-2B	121	3.3	57	-83	-8	148	138
10-7A	123	3.3	51	-81	-7	139	134
10-7B	120	3.3	63	-79	-8	150	152
10-8A	119	3.3	53	-68	-9	130	118
10-8B	121	3.3	67	-60	-9	136	99
10-13	121	3.3	44	-70	-8	122	127
10-23A	119	3.3	47	-63	-6	116	129
10-23B	122	3.3	17	-66	-6	89	85
4-21	75	3.5	53	31	7	15	24
4-29	71	3.5	54	33	5	16	28
5-6	72	3.5	62	31	7	24	26
5-14	75	2.9	49	27	7	15	22
5-15	81	2.9	48	23	5	20	6
5-28	80	2.9	52	25	6	21	3
6-3	72	2.9	63	31	3	29	22
6-4	73	2.9	67	36	3	28	23
7-15	-1	2.8	51	198	28	-175	-102
7-29A	+1	2.8	51	219	28	-196	-169
7-29B	+1	2.8	51	226	27	-202	-157
7-31	+4	2.8	51	239	31	-219	-243
8-5A	+2	2.8	51	231	30	-210	-230
8-7A	+3	2.8	51	223	31	-203	-199
8-7B	+2	2.8	51	219	27	-195	-164
10-21	+4	3.2	51	196	29	-174	-183
8-14	-17	2.8	51	277	38	-264	-305
8-25	-19	2.8	51	277	35	-261	-298
8-27A	-20	3.2	51	239	32	-260	-207
8-27B	-21	3.2	51	246	35	-230	-239
9-9	-31	3.2	51	276	42	-267	-299
9-10	-31	3.2	51	273	41	-263	-281
9-17	-31	3.2	51	274	38	-261	-292
11-4	-31	3.2	51	274	41	-264	-276

$$\bar{Q}_b'/t = 0.60 \bar{Q}_m/t - 0.08(0.60 \bar{Q}_m/t) = 0.55 \bar{Q}_m/t \quad (7)$$

When 50 Cal./sq.m./hr. is used as the metabolic heat production of a sitting resting man, \bar{Q}_b'/t equals 51 Cal./hr.

To calculate \bar{Q}_g'/t , the following equation is used:

$$\bar{Q}_g'/t = \frac{3.09(\bar{T}_c - T_o)}{I} (2.26) + \bar{Q}_{h+f}/t \quad (11)$$

Where:

\bar{T}_c is the standard average barrier coverall temperature for any given operative temperature.

2.26 is the standard heat transfer surface of the barrier coverall.

\bar{Q}_{h+f} is the standard rate of heat leakage through the gloves and footgear for any given operative temperature, when the insulation is equivalent to approximately 1.0 and 2.5 clo, respectively.

Values for \bar{T}_c at different operative temperatures were obtained from the experimental data. Since, as noted, T_c varies with changes in the difference between $\Delta H_v'/t$ and Q_o'/t , the \bar{T}_c for a given operative temperature was determined by averaging only the T_c 's for those experiments that were in "thermal balance"; i.e., in which there was no evidence of physiological strain, and in which $\Delta H_v'/t$ approximated Q_o'/t . It was thought that values for \bar{T}_c so obtained would be independent of operative temperature and ventilating air temperature. As Table 9 shows, this proved to be only approximately true. At 180° F. (inlet air temperature 45-65° F.) \bar{T}_c was $86 \pm 2^\circ$ F., while at -30° F. (inlet air temperature 120° F.) it was $95 \pm 1^\circ$ F. However, it is to be noted, that if, instead of the determined \bar{T}_c , an average \bar{T}_c of 90° F. were to be used for all operative temperatures, the resulting error in the determination of \bar{Q}_g'/t at 180 and -30° F. would be only 5% and 3%, respectively.

Values for \bar{Q}_{h+f} were also obtained only from "balanced" experiments. This eliminated the low values due to low hand and foot temperatures in those experiments in the cold in which insufficient heat was provided the system. The values for \bar{Q}_{h+f} correspond approximately to the equation:

$$\bar{Q}_{h+f} = 30 - 0.32 T_o \quad (12)$$

TABLE 9

T_o °F.	\bar{T}_c °F.	\bar{Q}_{h+f} Cal./hr.
180	86±2	-26
120	86±2	-7
75	88±1	5
0	93±2	30
-20	94±2	36
-30	95±1	41

The average $\bar{Q}\sigma'/t$ and $\Delta H_v'/t$ for the balanced experiments at the different operative temperatures and the $\bar{Q}\sigma'/t$ are given in Table 10. As expected, average $\bar{Q}\sigma'/t$ and $\bar{Q}\sigma'/t$ are almost identical. Only in those experiments at low ambient temperatures, where $\Delta H_v'/t$ was slightly greater than what was calculated to be necessary, is there any appreciable difference between $\Delta H_v'/t$ and $\bar{Q}\sigma'/t$.

C. The Variation of $\bar{Q}\sigma'/t$ with Temperature, Insulation, and Activity.

In Figure 1, $\bar{Q}\sigma'/t$, or, as it may be called, the predicted $\Delta \bar{H}_v'/t$, is plotted against the difference between average barrier coverall temperature and operative temperature per unit clo, for activity levels corresponding to a sitting resting man, moderate work and hard work. The three lines fit the equation:

$$\bar{Q}\sigma'/t = \bar{Q}_b'/t - 7.95 \frac{(\bar{T}_c - T_o)}{I} \quad (13)$$

for \bar{Q}_m/t of 92, 224, and 426 Cal./hr. The average corrected experimental values for $\Delta H_v'/t$ for the "balanced" experiments at different operative temperatures are shown by the points on the graph. They correspond very closely to the $\bar{Q}_m/t = 92$ line. It is to be noted that the slope of the lines is not equal to the product, $kgA_c (3.09 \times 2.26 = 7.0)$ because of the correction for \bar{Q}_{h+f} (equations 9 and 12). The intercept of the $\bar{Q}_m/t = 92$ line at $\bar{Q}\sigma'/t = 0$ corresponds to a $(\bar{T}_c - T_o)/I$ of 6.5; that is, $\bar{T}_c - T_o$ is 22° F. when the insulation is 3.3 clo. If \bar{T}_c is taken as 87° F., T_o is 65° F. when $\bar{Q}\sigma'/t$ is zero. This does not mean that there should be no air flow at this temperature, but rather that the ventilating air need only evaporate the perspiration to maintain thermal equilibrium.

D. The Extent of the Body Surface Ventilated.

It was felt that experiments to determine the minimum fraction of the total body surface which must be ventilated to maintain thermal balance were unnecessary. Extreme air temperature and very high flows are impractical; therefore, when the difference between T_c and T_o is large,

TABLE 10
STANDARD VALUES FROM "BALANCED" EXPERIMENTS

Exp. No.	T ₀	I	T _c -T ₀	$\Delta H_v'/t$	Q _v /t	Q _a /t	$\Delta H_v'/t - Q_a/t$
	°F.	Cal	°F.	Cal/hr.	Cal/hr.	Cal/hr.	Cal/hr.
9-15B	184	3.3	-96	297	273		
9-23B	179	3.3	-94	301	279		
9-24A	178	3.3	-89	261	265		
9-26A	186	3.3	-101	311	298		
9-26B	186	3.3	-100	324	293		
10-1A	180	3.3	-98	282	287		
Ave.	182±3	3.3	-96±4	296±17	283±10	281	+15
10-2B	121	3.3	-37	138	148		
10-7A	123	3.3	-38	134	139		
10-7B	120	3.3	-36	152	150		
10-8A	119	3.3	-32	118	130		
10-13	121	3.3	-33	127	122		
10-23A	119	3.3	-30	129	116		
Ave.	121±1	3.3	-35±3	133±8	134±11	132	+1
4-21	75	3.5	15	24	15		
4-29	71	3.5	17	28	16		
5-6	72	3.5	15	26	24		
Ave.	73±2	3.5	16±1	26±1	18±4	14	+12
5-14	75	2.9	12	22	15		
6-3	72	2.9	13	22	29		
6-4	73	2.9	14	23	28		
Ave.	73±1	2.9	13±1	22±0	24±6	17	+5
7-31	4	2.8	92	-243	-218		
8-5A	2	2.8	89	-230	-209		
8-7A	3	2.8	88	-199	-202		
Ave.	3±1	2.8	90±2	-224±17	-210±5	-205	-19
10-21	4	3.2	90	-183	-173	-176	-7
8-14	-17	2.8	111	-305	-263		
8-25	-19	2.8	111	-298	-260		
Ave.	-18±1	2.8	111±0	-302±4	-262±2	-262	-40
8-27B	-20	3.2	115	-239	-229	-237	-2
9-9	-31	3.2	127	-299	-266		
9-10	-31	3.2	126	-281	-262		
9-17	-31	3.2	127	-292	-260		
11-4	-31	3.2	125	-276	-263		
Ave.	-31	3.2	126±1	-287±9	-263±2	-262	-23

the body area ventilated must be maximal to fulfill the steady state heat requirement. This is confirmed by Marbarger's observation (5) that, at 165° F., ventilation of the trunk and head was insufficient to maintain comfort.

E. Variation of the Insulation between Skin and Ventilating Air.

If the insulation between the skin and the ventilating air is increased, the difference between skin temperature and ventilating air temperature must be greater if the sensible heat loss to the ventilating air is to remain the same. Therefore, for the same $\Delta H_v'/t$ a greater range of inlet air temperature will be required. Also, if the total amount of clothing worn is the same, the insulation over the ventilating air will be reduced correspondingly, and Q_g'/t will be greater. Thus, the minimum insulation between air and skin, compatible with a practical clothing assembly, is desirable.

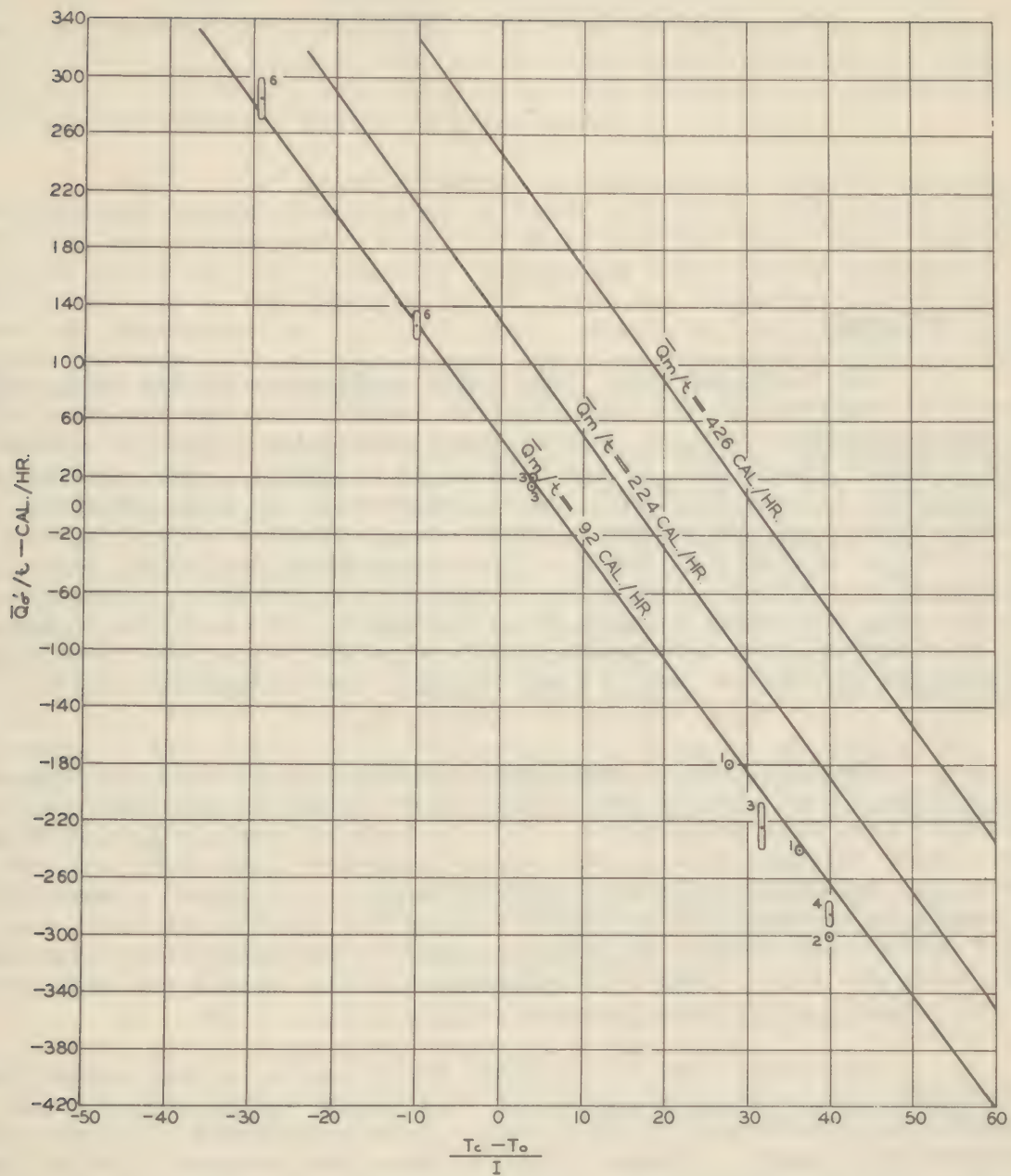


FIGURE 1

THE \bar{Q}_s/t FOR THREE METABOLIC LEVELS IS PLOTTED AGAINST THE TEMPERATURE DIFFERENCE BETWEEN THE BARRIER COVERALL AND THE OPERATIVE TEMPERATURE PER CLO. THE CIRCLED DOTS ARE THE AVERAGE $\Delta H'_s/t$ FOR THE "BALANCED" EXPERIMENTS. THE NUMBERS REPRESENT THE NUMBER OF EXPERIMENTS IN EACH GROUP

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VI. PROTECTION OF THE EXTREMITIES FROM COLD

A. Rationale.

The hands and feet limit human performance in the cold, with very few exceptions. The hand requires nearly twice the thickness of insulator as the trunk, to provide equal protection. Such thicknesses are patently impossible, if the hand is to be useful. Full insulation of the foot is very difficult, partly because of the high pressures, and partly because of the necessary mechanical strength of the footgear. It occurred to us that physiological protection might be latent, and not generally recognized--especially in view of the dearth of gloves and boots among the animal kingdom in cold regions. The experiments described in this section were undertaken to determine whether or not such latent protection does exist, and, if so, to begin the exploration of its extent.

When the rate of heat loss from the body exceeds the rate of heat production, blood flow to the surface is curtailed in an effort to maintain deep body temperature. This is most apparent in the hands and feet where vasoconstriction may result in severe discomfort, and even freezing, before there is any appreciable drop in internal temperature. Attempts to prevent this by artificial heating of only the hands and feet are unsound because reflexes responsible for vasoconstriction and shivering are lost. Deep body temperature falls rapidly and produces uncontrollable shivering of central origin (15).

Arteriolar tone is regulated by autonomic nervous system impulses reflecting the body's heat state; by circulating vasoconstrictor and vasodilator substances; by the direct and reflex effects of local tissue temperature changes. Freeman (16) has shown that autonomic control is dominant in the hands; hence, that blood flow is determined by the need of the body to conserve or dissipate heat. This is also demonstrated by the experiments of Abramson and Ferris (17) in which reactive hyperemia in the hands could repay only 10-20% of the theoretical oxygen debt, while in the forearm and leg the entire calculated debt was repayed. Ferris, et al (18) have shown that the blood flow in the artificially heated hand of a lightly clothed subject at an ambient temperature of 62° F. is only slightly greater than in the non-heated hand. In contrast, when the body is warm, blood flow increases to 20-40 times that when the

hand only is heated. Spealman (19) demonstrated in 3 subjects that, when the body was uncomfortably warm, blood flow through the hand immersed in cold water (36° F.) was 4.5-8.2 cc./100 cc. hand volume/min. as compared to 1.5-2.5 cc./100 cc. hand volume/min. when the body was uncomfortably cold but the hand was heated in water at 95° F.

Miller (20) recently demonstrated that the rabbit's ear could be protected against freezing for 2 hours at -55° F. if the rest of the body was warm. Spealman's data (21) show that the human foot immersed in cold water was kept warmer by heating the body than by increase of the insulation of the immersed foot. Lewis and Pickering in 1931 (22) reported experiments at 60° F. in which heating the body caused a significant increase of hand temperature. Similar experiments with the hands exposed to lower air temperatures could not be found.

All these results establish the dominance of autonomic control of arteriolar tone in the extremities. But the extent and significance of the dominance apparently has not been fully appreciated, at least for human extremities. Investigation of this requires separate control of the thermal states of the body, and of the extremities. The ventilating system described has made it possible to supply the body with as much or as little heat as was desired at temperatures as low as -30° F. The hands and feet, excluded from the ventilating air circuit, received heat only from their blood supply. From their temperatures, it was possible to determine whether or not the blood flow to the extremities was regulated by the need of the body to conserve or to dissipate heat; or was primarily determined by the known direct effect of cold upon blood vessels. Experiments were planned to investigate the following specific points:

- 1) The effect upon hand and foot temperatures of heat supplied to the rest of the body in amounts adequate and inadequate for thermal balance.
- 2) The effect of warming the body upon the temperature of extremities which had become cold.
- 3) The differences in temperature response between hands and feet.
- 4) The effect of reducing the insulation of the hand upon its temperature when the body is in thermal equilibrium.

B. Experimental Procedure.

Experiments were performed at controlled, ambient temperatures, at about 0, -20 and -30° F. upon three young adult males in apparent good health. Calculations of $\Delta H_V'/t$ and of Q_{σ}'/t were made as described

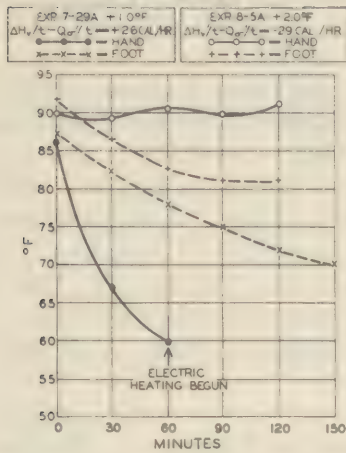
in Section III-B. The thermal state of the system was determined by comparing $\Delta H_v'/t$ with Q_{σ}'/t . (It will be recalled that the difference, $\Delta H_v'/t - Q_{\sigma}'/t$ is negative when the system receives more heat than it loses, and positive when there is a net heat loss.) The insulation of the footgear, calculated in clo, was 2.6. Gloves of 1.0 equivalent clo were worn. In some experiments one glove was replaced with a rayon insert, the insulation of which was equivalent to 0.25 clo. In other experiments one hand was bared. Insulation of the air was 0.7 clo. Average hand and foot temperatures were measured as described in Section III-B.

C. Results.

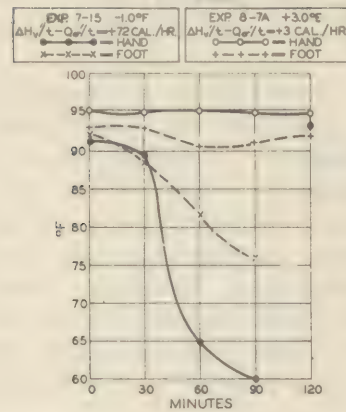
1. The Effect upon Extremity Temperatures of Variation of the Heat Supplied. Figures 2 and 3 illustrate, in two subjects at approximately 0° F., the effect upon hand and foot temperatures of heat, adequate and inadequate for thermal equilibrium. In Figure 2 it is seen that when the heat deficit was 26 Cal./hr., the average hand temperature fell to 60° F. within 60 minutes, and electrical heating of the hands was necessary to allow the experiment to continue. The average foot temperature dropped to 70° F. in 2-1/2 hours. However, when the system received an excess of 29 Cal./hr., average hand temperature was sustained above 90° F., and average foot temperature between 80-85° F. Essentially the same response is apparent in Figure 3. When the net heat loss was 72 Cal./hr., average hand temperature dropped to 60° F., and foot temperature to 75° F. within 90 minutes. When the rate of heat supplied to the system equalled the rate of heat loss, both the average hand and foot temperatures were maintained above 90° F. Two additional experiments (not graphed, see Tables 5, 8 and 10) at +4° F. confirm these results. In one (Exp. 7-31) 25 Cal./hr. more than required were supplied, and average hand temperature remained about 90° F., with average foot temperature about 88° F. throughout the four hour experimental period. In the other (Exp. 10-21) the heat surplus was 10 Cal./hr., and average hand and foot temperatures were maintained between 86 and 94° F.

Average hand and foot temperatures at about -30° F. are given in Figure 4 for three experiments, in which there were net heat gains of 19 to 33 Cal./hr. Average hand temperatures were all between 84 and 94° F. (The low initial hand temperature in Exp. 9-17 resulted from a delay in turning on the ventilating air.) Average foot temperatures in Exps. 9-9 and 9-10 varied between 80 and 90° F. In Exp. 9-17, average foot temperatures were lower, with two readings slightly below 70° F., the usual minimum comfort level. However, the feet remained comfortable and the temperature trend in the last 90 minutes was gradually upwards. In another experiment $\Delta H_v'/t$ and Q_{σ}'/t were nearly equal; the average temperature of the hands stayed above 90° F., and the average foot temperature above 80° F.

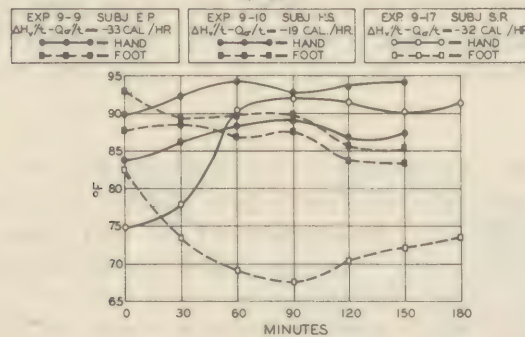
To = 0°F SUBJ SR



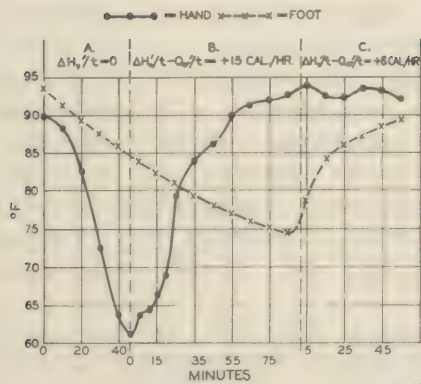
T₀ = 0°F SUBJ. RQ



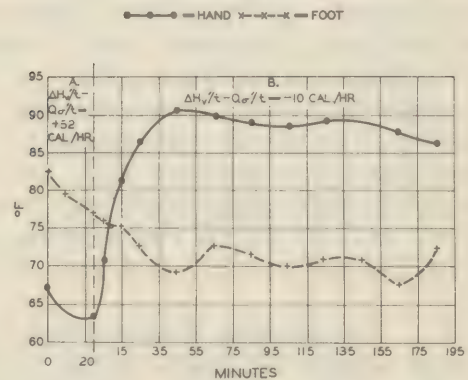
$T_0 = -30^\circ\text{F}$



EXP. 10-27
To=0°F SUBJ. E.P.



EXP. 8-27
To = -20°F SUBJ. E.P.



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Essentially the same results were obtained in two experiments (not graphed, Tables 6 and 8) at -20°F . In one (Exp. 8-14) an excess of 42 Cal./hr. was supplied; average hand and foot temperatures were maintained between 85 and 90°F . for 3-1/2 hours. In the other (Exp. 8-25) the excess was 38 Cal./hr.; average hand temperature varied between 76 and 83°F ., and average foot temperature between 80 and 83°F .

2. The Effect of Warming the Body upon Cold Extremities. Figure 5 is the graph of an experiment at 0°F . in which no heat was supplied for 45 minutes. Average hand temperature fell to 61°F . and average foot temperature from 93 to 86°F . Heating was then begun, which reduced the net heat loss rate to 15 Cal./hr. Average hand temperature began to rise almost immediately and reached 90°F . within 55 minutes. Average foot temperature, however, continued to fall to 75°F . At the end of 85 minutes, and concomitant with a reduction in the net heat loss to 6 Cal./hr., the average foot temperature began to rise, and was 89°F . when the experiment was terminated.

An experiment at -20°F . is shown in Figure 6. During the initial period the net heat loss rate from the system was 52 Cal./hr. Average hand temperature fell to 63°F ., and average foot temperature to 76°F . When an excess of 10 Cal./hr. was supplied, average hand temperature began to rise immediately and reached 90°F . within 45 minutes. Average foot temperature, however, fell to 70°F . for the remainder of the experiment.

Figure 7 is the graph of an experiment at -30°F . in which no heat was furnished during the first ten minutes. When average hand temperature reached 58°F ., an excess of 46 Cal./hr. was supplied. After a delay of 25 minutes, average hand temperature rapidly rose to $90-95^{\circ}\text{F}$. Average foot temperature fell to 72°F . during the first 50 minutes of the heating period and then rose to 85°F . Figure 8 is the graph of a second experiment at -30°F ., during which no heat was given for 35 minutes. Average hand temperature fell rapidly to 55°F . Average foot temperature fell to 82°F ., when an excess of 18 Cal./hr. was delivered; average hand temperature rose quickly and reached 85°F . in 30 minutes. However, foot temperatures continued to drop slowly for 55 minutes after the onset of heating, then began to rise, and had returned to 88°F . by the end of the experiment. In one experiment at -30°F ., as shown in Figure 9, the extremities did not rewarm; average hand temperature fell to 58°F . in 25 minutes. An excess of 39 Cal./hr. was then supplied, yet average hand temperature continued to drop, to 46°F . in the ensuing 55 minutes. Average foot temperature also continued to fall and was 66°F . at the end of the experiment.

3. Difference between the Temperature Response of the Hands and Feet. When the supply of heat to the system exceeded the rate of heat loss, both the hands and feet were kept within the comfort range, i.e., above 70°F . In general, however, the average temperature of the feet was

FIGURE 7

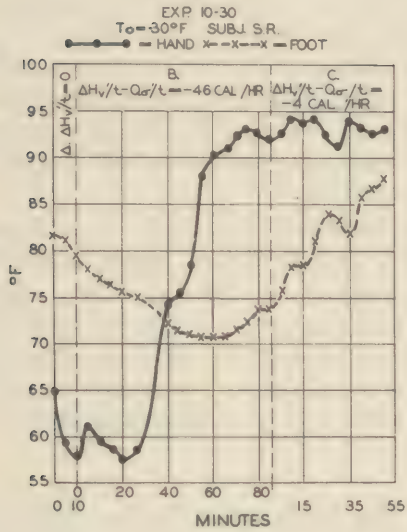


FIGURE 8

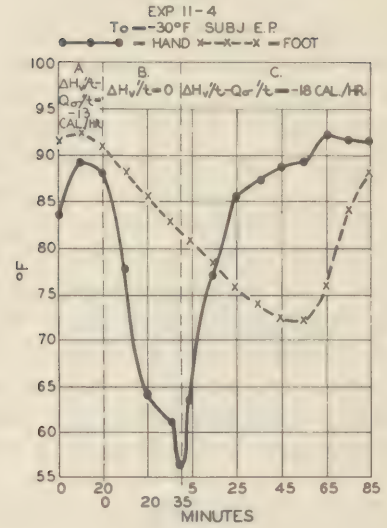


FIGURE 9

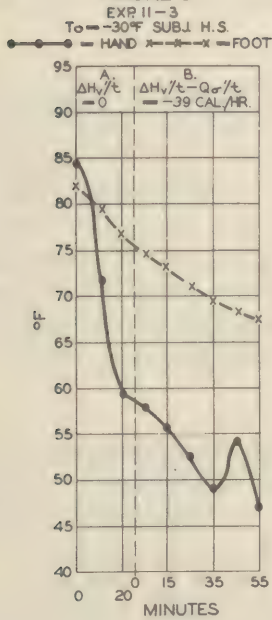
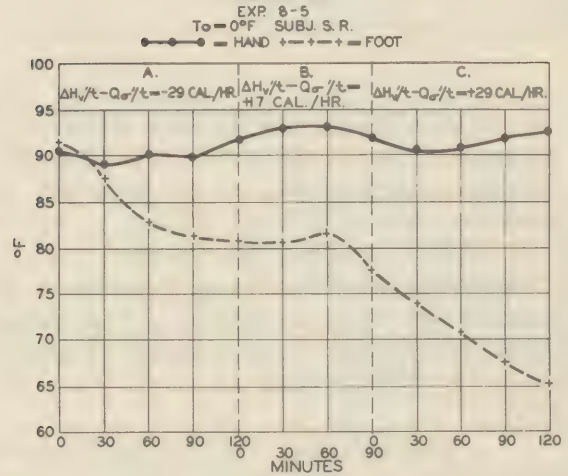


FIGURE 10



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lower than that of the hands despite the greater insulation of the footgear. In some experiments this temperature difference was only about 5° F. (Exp. 8-7A, Fig. 3, Exp. 9-9, Fig. 4, Exp. 9-10, Fig. 4). In others, it was as much as 10-20° F. (Exp. 8-5A, Fig. 2, Exp. 9-17, Fig. 4, Exp. 8-27, Fig. 6). When the net heat loss from the system was large, both hands and feet cooled; but the rate of cooling of the hands was greater than that of the feet. Since, in this circumstance, the arterioles of both the hands and the feet are constricted, the slower fall of foot temperature is the result of the heavier insulation of the footgear, and the smaller surface area per mass of the foot.

Figure 10 is the graph of an experiment at 0° F. in which a small net heat loss resulted in a fall of average foot temperature but not of average hand temperature. In period A, 29 Cal./hr. excess were furnished, and hand temperature was maintained at about 90° F., with foot temperature at about 82° F. In periods B and C, the heat supply was reduced so that deficits were 17 and 21 Cal./hr., respectively. Average hand temperature continued above 90° F., but average foot temperature fell steadily to 65° F.

When the body was heated after the extremities had been allowed to become cold, foot temperature usually continued to drop until the hands had completely rewarmed. Figures 4, 5 and 7 show a lag of 60-80 minutes between the initial rise of the hand and the foot temperatures. Only a very small part of this lag may be attributed to the greater heat capacity of the footgear, since the heat calculated to rewarm the boot, when the temperature of the inside is raised from 70 to 90° F., is of the order of magnitude of 1 Cal. In experiment 8-27, Figure 6, warming the body resulted in a rise of hand temperature only, the average foot temperature stabilized at about 70° F.

4. The Effect of Exposure of the Hand to Strong Cold Stimulus. In ten experiments the direct effect of cold upon the hand was intensified by substituting a rayon insert (insulation equivalent to 0.25 clo) for the glove on one hand, or by removal of the glove. The subject was allowed to move the hand at will, but not to touch the metal of the chair. With the body in thermal equilibrium, the changes in average hand temperature resulting from this sudden and almost complete loss of insulation were followed. The results are summarized in Table 11, and the individual experiments (except Exp. 8-25) are plotted in Figures 11, 12, 13, 14, 15 and 16.

One subject (E.P.) maintained average hand temperature above comfort level in every experiment. In Figure 11 an experiment is graphed in which his hand was bare for 95 minutes at 0° F. In general, hand temperature stayed between 70 and 80° F. Figure 14 is the graph of two experiments in which the rayon insert was worn, at -20° F. and -30° F. In both, average hand temperature was maintained above the comfort level. In Figure 16 an experiment is plotted in which the hand was bared for

TABLE 11

Subj.	Exp.	T _o	Insulation	$\Delta H_v'/t - Q_{cr}'/t$	Effect Upon Average Hand Temperature.
		°F.		Cal./hr.	
S.R.	10-21	0	Hand bare	-10	Maintained at comfort level.
E.P.	10-27	0	Hand bare	+8	Maintained at comfort level.
H.S.	10-28	0	Hand bare	—	Temperature fell to below 55°F., but rose to comfort level when heat supply to the body increased.
E.P.	8-27	-20	Rayon insert	-10	Maintained at comfort level.
S.R.	8-25	-20	Hand bare	-38	Temperature fell, hand painful after several minutes.
E.P.	9-9	-30	Rayon insert	-33	Maintained at comfort level.
S.R.	9-17	-30	Rayon insert	-32	Temperature fell on first try, but maintained at comfort level on second try.
H.S.	9-10	-30	Rayon insert	-19	Temperature fell on two attempts, but each time returned quickly to comfort level when glove replaced.
S.R.	10-30	-30	Hand bare	+20	Maintained at comfort level.
E.P.	11-4	-30	Hand bare	-13	Maintained at comfort level.

60 minutes at -30° F. The hand remained completely comfortable; average hand temperature was sustained at about 70° F. A first experiment (8-25, Table 6 and 11) on subject S.R. was performed with the hand bared at -20° F. Although there was an excess of 36 Cal./hr., the temperature of the hand fell rapidly and the experiment was terminated. Figure 13 is the graph of a second experiment on subject S.R. When the rayon insert was first substituted for the glove, average hand temperature fell rapidly to 50° F. Since it quickly returned to control level when the glove was replaced, the rayon insert was substituted a second time. In this period, average hand temperature was maintained above 70° F. for 50 minutes. In a third experiment (Figure 11) the hand was bared for 95 minutes at 0° F. After an initial drop to 70° F., average hand temperature rose to 85° F. and remained at this level. The fourth experiment (Fig. 16) was performed with the hand bared at -30° F. Average hand temperature stayed between 75 and 80° F. throughout the 60 minute period.

Subject H.S. has been used in only two experiments to date. In the first of these at -30° F. (Figure 15) two attempts to maintain hand temperature wearing only the rayon insert were unsuccessful. Hand temperature fell rapidly, but each time returned to control level within 10 or 15 minutes after the glove was replaced. The second experiment was performed at 0° F. with the hand bared (Figure 12). Hand temperature fell to between 50 and 55° F. and the subject noticed pain in the finger tips. It was then discovered that the air tube to the trunk had been accidentally disconnected and this area was receiving no warm air. When the tube was reconnected, average hand temperature began to rise almost immediately and in the next twenty minutes increased by more than 20° F.

5. Finger and Toe Temperature Response. The above results are intended to show the general pattern of the temperature responses of the extremities, rather than to give a detailed account of fluctuations which may occur over short periods, especially in the fingers and toes. Therefore, only average hand and foot temperatures have been graphed, and temperature readings have been plotted at from 5 to 30 minute intervals. However, in most of the experiments finger and toe temperatures (on the opposite extremity) were also followed and frequent readings were taken, sometimes at 30 second intervals. In general, the relations between finger temperature and average hand temperature, and toe temperature and average foot temperature were as follows:

- a. When the hands were warm, finger and average hand temperatures were usually within one or two degrees of each other.
- b. When the hands were allowed to become cold, the rate of fall of finger temperature was greater than that of average hand temperature; often cycling of the finger temperatures could be observed during the period of hand cooling.

FIGURE 11

$T_o = 0^\circ\text{F}$

EXP 10-21—SUBJ. S.R.
 $\Delta H_r/\tau - Q_{\sigma}/\tau = -10 \text{ CAL./HR.}$
EXP 10-27—SUBJ. E.P.
 $\Delta H_r/\tau - Q_{\sigma}/\tau = +8 \text{ CAL./HR.}$

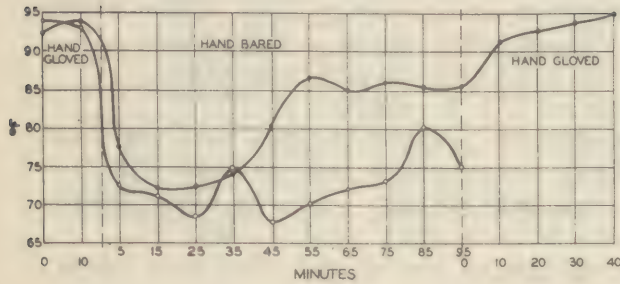


FIGURE 13

EXP 9-17

$T_o = -30^\circ\text{F}$ —SUBJ. S.R.
 $\Delta H_r/\tau - Q_{\sigma}/\tau = -32 \text{ CAL./HR.}$

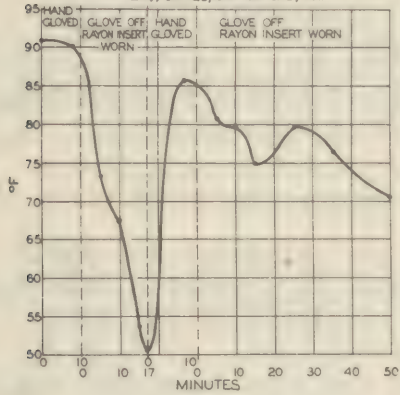
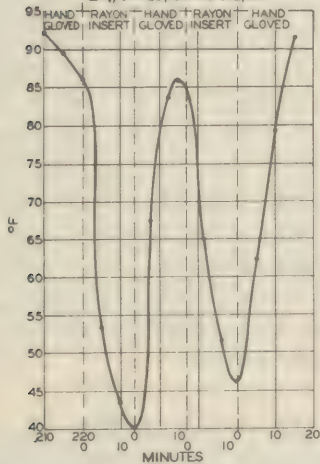


FIGURE 15

EXP 9-10

$T_o = -30^\circ\text{F}$ —SUBJ. H.S.
 $\Delta H_r/\tau - Q_{\sigma}/\tau = -19 \text{ CAL./HR.}$



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FIGURE 12

EXP 10-28

$T_o = 0^\circ\text{F}$ —SUBJ. H.S.

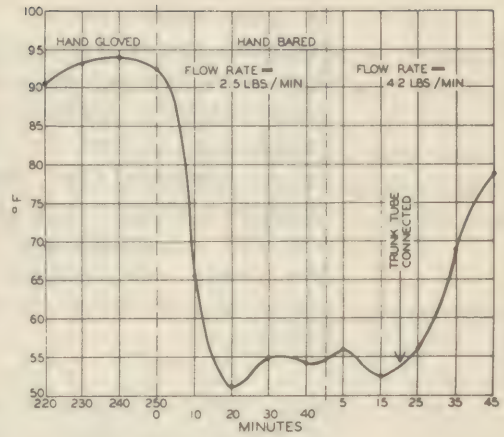


FIGURE 14

EXP 9-9—SUBJ. E.P.
 $\Delta H_r/\tau - Q_{\sigma}/\tau = -33 \text{ CAL./HR.}$
 $T_o = -30^\circ\text{F}$
EXP 8-27B—SUBJ. E.P.
 $\Delta H_r/\tau - Q_{\sigma}/\tau = -10 \text{ CAL./HR.}$
 $T_o = -20^\circ\text{F}$

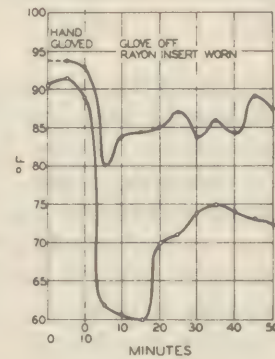
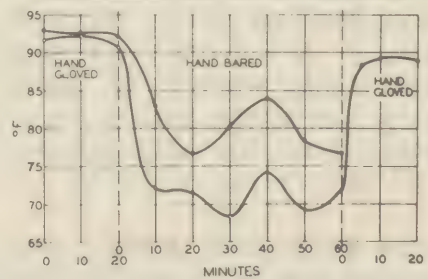


FIGURE 16

$T_o = -30^\circ\text{F}$

EXP 10-30—SUBJ. S.R.
 $\Delta H_r/\tau - Q_{\sigma}/\tau = +20 \text{ CAL./HR.}$
EXP 11-4—SUBJ. E.P.
 $\Delta H_r/\tau - Q_{\sigma}/\tau = -13 \text{ CAL./HR.}$



- c. When the hands were rewarmed by heating the body, the initial rise in finger temperature was always greater than average hand temperature, and returned to comfort level sooner.
- d. In some experiments there was considerable variation between great toe temperature and average foot temperature when the latter was at the comfort level. Great toe temperatures seemed to be less stable and sometimes would cycle from as much as 10° F. above, to 25° F. below average foot temperature. Usually this cycling was observed when average foot temperature was between 70 and 75° F. or while it was decreasing. In one experiment the great toe temperature of one foot fell to 44° F., while the average temperature of the other foot was above 80° F.
- e. When the foot was allowed to cool, the rate of fall of great toe temperature was greater than average foot temperature. When the feet were rewarmed, great toe temperature returned to its control level as much as 10 minutes before average foot temperature.

D. Discussion.

These experiments clearly demonstrate that, at least to -30° F., regulation of the blood flow to the extremities is primarily determined by the thermal state of the body. Vasoconstriction need not occur provided that the body does not have to conserve heat. If it does occur, it may be taken as an indication that the body is attempting to conserve heat. Under conditions comparable to these experiments, artificial heating of the hands and feet is unnecessary; they will be adequately heated by their blood supply. However, in every experiment in which there was a net heat loss of greater than about 25 Cal./hr., vasoconstriction occurred in both the hands and feet, and these parts became cold. It is important to note that the supply of a large but still inadequate amount of heat to the body area was almost as ineffective in protecting the non-heated extremities as the failure to supply any heat at all. (Compare the rate of cooling of the hand in Figures 2, 3, and 5 and in Figures 6 and 8.) This observation is confirmed by the example of the electrically heated suit, in which failure of the power supply to a glove or foot insert will result in rapid cooling of the affected extremity despite the considerable amount of heat being supplied to the rest of the body.

It is well known that blood flow through the extremities is greater when the body is overheated than when it is in thermal balance. In most of these experiments the system received 5-15% (10-40 Cal./hr.)

more heat than was calculated as being lost. Since the error in determining both $\Delta H_V'/t$ and $Q\sigma'/t$ may equal 5%, the degree of overheating in most instances was probably not significant. In several successful experiments, $\Delta H_V'/t$ and $Q\sigma'/t$ were about equal. Therefore it would appear that overheating is not essential to sustain blood flow through the non-heated extremities at temperatures down to -30° F.

The experiments in which the extremities were rewarmed demonstrate that adequate heating of the body alone not only can prevent peripheral vasoconstriction but often can reopen constricted vessels in cold extremities. After a fall to $55-60^\circ$ F., hand temperature may return to control level in 20 to 50 minutes. No satisfactory explanation can be offered for the failure of the extremities to rewarm in one experiment. It emphasizes the need for further experiments.

It is a common experience for the feet to feel cold while other body areas are comfortable. The data of Roth, Horton and Sheard (23) prove that the temperature of the toes is the first to drop when the body starts to cool and the last to rise when it is warmed. The differences in the temperature response between the hands and feet in our experiments are in agreement with this observation. Figure 10 clearly shows the fall of foot temperature but not of hand temperature which occurs when the net heat loss from the system was small. In the rewarming experiments, average foot temperatures continued to fall until hand temperatures had returned to normal.

That the temperature of the bare hand at -30° F. was sustained above 70° F. is dramatic evidence that the vasoconstrictive effect of severe cold is subordinate to the autonomic control of arteriolar tone in the hand. This is not to say that the cold stimulus is without effect. Hand temperature invariably fell when the insulation was removed, then levelled off between 70 and 85° F. (i.e., 5 to 20° F. below the level with the glove on). The appearance of the hand was interesting, for there was no marked deepening of color or reddening, such as is usually seen when skin is exposed to cold. The reason for the failure of hand temperature to stabilize in three experiments is not known. It is our impression that tenseness or anxiety about the experimental procedure contributed to the failure. That such feelings may be accompanied by peripheral vasoconstriction is recognized. In two of the unsuccessful attempts the temperature of a finger on the opposite hand - the hand which had remained gloved - also dropped sharply (from 88° F. to 65° F. in one experiment and from 90° F. to 58° F. in the other). Of practical importance was the fact that replacement of the glove always brought about a prompt return of hand temperature to the comfort level.

The purport of these results is that the temperature of the extremities can be made nearly independent of the ambient temperature

and of insulation, over a wide range; and dependent primarily upon the thermal state of the rest of the body. The practical implications are many, and obvious. For example, in the standard Air Force electrically heated suit 37% of the wattage goes to the gloves and boots, whereas the area of the hands and feet is only 15% of the body area. Relatively more of this power is wasted than from the trunk and limbs, because of the lesser insulation of gloves and boots, and the position of the heating elements. Transfer of this power to the trunk and limbs would appear to make the suit more efficient, cheaper to manufacture, and more durable. At present, the electrically heated suit keeps the hands and feet comfortable by artificial heat, while the rate of fall of deep body temperature is slowed by supply of part of the required heat. (Evidence that the rectal temperature may fall one or two degrees in two hours at -40° F. is found in the report of Taylor and Hall from this laboratory (24).) This, of course, is acceptable only for short exposures.

It has been the universal practice of applied physiology so to modify the environment that it is tolerable to the man. Attempts to induce rapid adaptations or modifications of human physiology have met with little success. The observation that extremity temperature can be made relatively independent of the environmental temperature does offer the possibility of practical control of a physiological response.

Many problems, theoretical and practical, remain to be solved. Among the more important are; the analysis of the mechanisms; the extent of individual variation (with the derived possibility of use as a diagnostic tool); whether the state of the arterioles is determined by thermal level and/or by rate and direction of thermal state change; the lower limits of control, and the influence of conduction by solid objects upon these limits; and whether or not comparable control is possible at high temperatures. (Data at hand indicate that this is possible.)

VII. ENGINEERING DATA

A. Applications of Ventilated Clothing.

The forced internal ventilation of clothing in effect dissociates the man from ambient thermal conditions, and from his outer clothing. Therefore, specialized clothing, protective or insulative, imposes no thermal stress upon him, and may be chosen on the basis of functional suitability. Equipment for maintaining proper thermal environment may be reduced to that necessary to condition only the space between the man and his outer clothing--of the order of one cubic foot. The principal limitation of ventilated clothing is the necessary connection of the man to a source of air. Therefore it will be useful only in situations where this connection will be of little encumbrance.

In hot environments, on environments which vary between hot and cold, and in environments which require impermeable outer clothing, this system offers unique possibilities for economical protection. In cold environments, its advantages must be weighed against those of electrically heated clothing. The latter has the advantage in that its control and supply equipment would be simpler, and wires certainly would be lighter and less bulky than an air hose. Also, as presently conceived, ventilated clothing is more wasteful of energy than is electrically heated clothing. Since the air issues from the clothing at about skin temperature, much of its available enthalpy is dissipated unless it exhausts into an enclosed space, such as an aircraft cabin. (Wastage could be greatly reduced by passing the air issuing from the barrier coverall progressively over the succeeding outer clothing layers; but this might entail prohibitive complications in the clothing construction.) The main advantage of ventilated clothing over electrically heated clothing in the cold is that disposal of body water vapor is complete.

B. The Estimation of Ventilating Air Requirements.

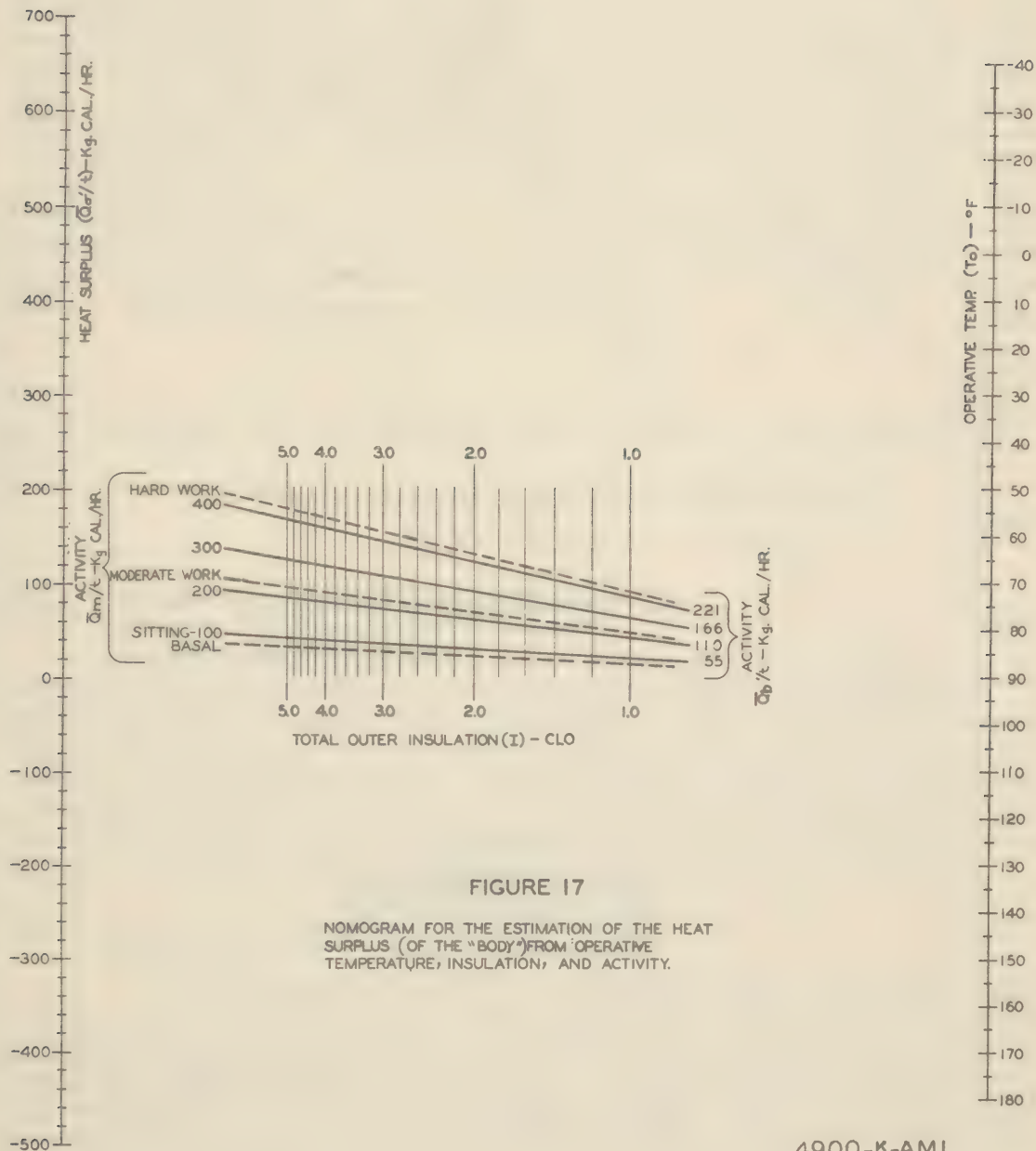
The estimation of ventilating air requirements may be properly divided into two steps: the estimation of the heat requirements, and the estimation of air temperature and flow rate to supply this. Figure

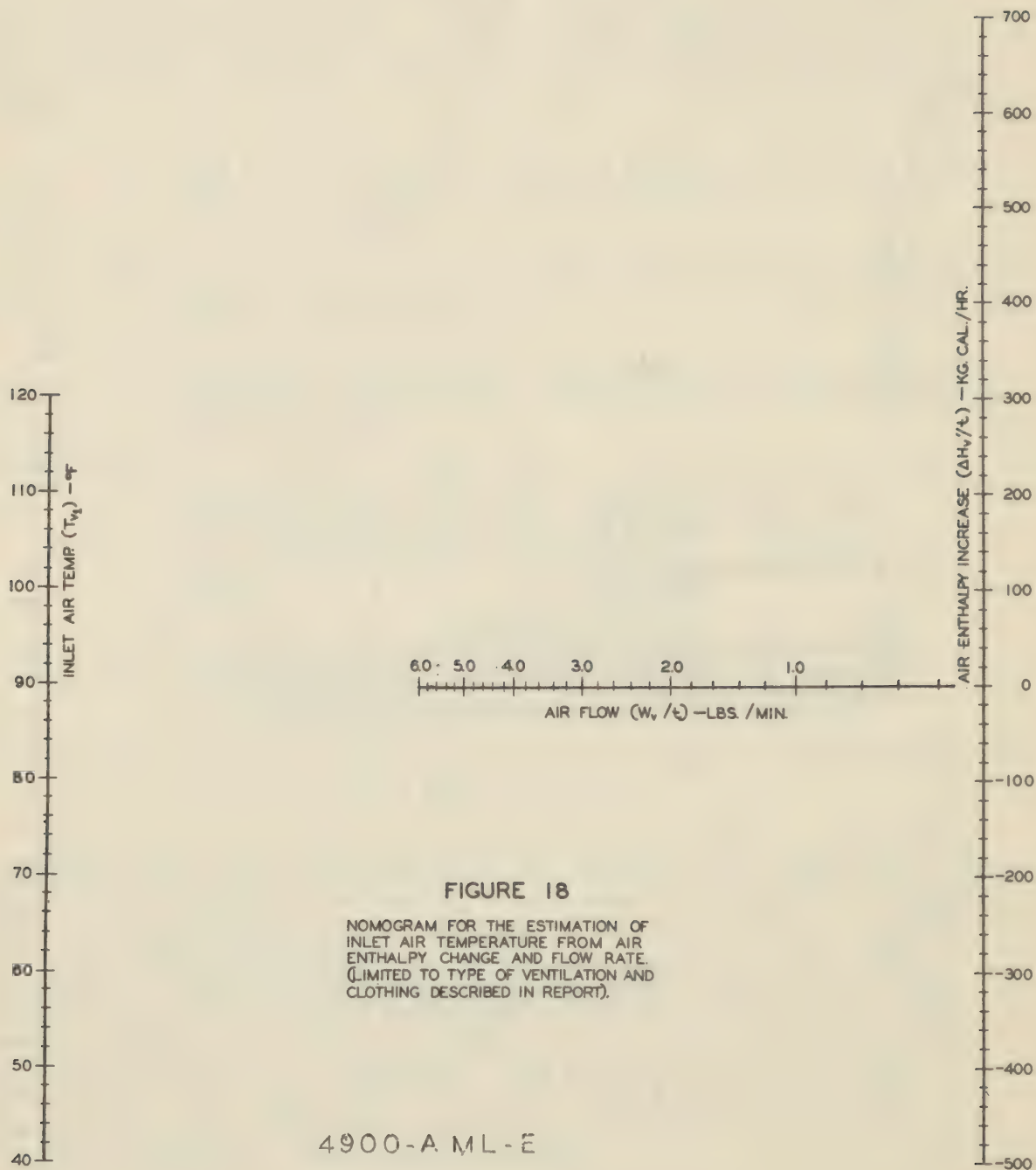
17 is a nomogram relating operative temperature, total insulation, and activity to the steady state heat surplus of the Air Force man "body", \bar{Q}_b'/t , (i.e., for the body minus the head, see Section IV-A.) This chart has been calculated from the experimental data, and its accuracy is approximately 10%. It is of general application; it is independent of the manner in which the heat is supplied, and of the type of clothing. However, it is valid only if the following conditions obtain:

- 1) The total insulation (clothing outside of the heat source plus air insulation) has been determined as described in Section II-B.
- 2) The heat source is separated from the skin by insulation of less than one half clo.
- 3) The area of the man is in the range of 1.75 to 1.90 sq.m. (However, a proportional correction may be applied; see Section III-B.)
- 4) The heat loss by evaporation is 40% of the total metabolic rate, if the \bar{Q}_m/t activity figures are used. (\bar{Q}_b'/t figures are also given for use in situations where this is not the case; see Section III-B.)
- 5) The insulation of the gloves plus air is between one-and-a-half and two equivalent clo, and the hands are not heated or cooled by contact with solid objects.
- 6) The insulation of the footgear plus air is greater than three equivalent clo.

To use the chart, the stated operative temperature is connected by a straight line to the intersection of the vertical line representing the appropriate insulation with that \bar{Q}_m/t line which corresponds to the given activity. The straight line is extended to intersect the heat surplus scale. The point of intersection is the heat surplus for the "body". For example, if the operative temperature is 0° F., and the man is to sit quietly with total outer insulation of 3.0 clo (2.3 from the outer garments plus 0.7 from the air) connect 0 on the right hand scale with the intersection of the vertical 3.0 line and the sloping 100 line. The intercept of the extension is at about -180 K_g.Cal./hr. on the heat surplus scale. Thus, this quantity of heat would have to be supplied to maintain a steady thermal state.

Figure 18 is for the estimation of approximate ventilating air temperature and flow rate from an air enthalpy change equal to the





steady state heat surplus. Thus, from the preceding example, if \bar{Q}'/t (equal $\Delta \bar{H}_v'/t$) is $-180 \text{ K}_g.\text{Cal.}/\text{hr.}$, and the air flow is to be $4.0 \text{ lbs.}/\text{min.}$, the extension of the line connecting an air enthalpy change of $-180 \text{ K}_g.\text{Cal.}/\text{hr.}$ with a flow of $4.0 \text{ lbs.}/\text{min}$ gives the air inlet temperature as 108° F. (Obviously, flow may be estimated from inlet air temperature and enthalpy change; or enthalpy change, from flow and temperature.) The nomogram is applicable only to the type of ventilation and clothing, and air flow distribution used in the experiments described. Heavier underwear, more efficient air distribution, etc., will alter these estimates. Furthermore, their error is appreciable because an empirical relation between ΔT_v and T_{v1} had to be derived to express $\Delta \bar{H}_v'/t$ in terms of the latter. (ΔT_v is not only difficult to measure, but is of no value to the engineer who must control the temperature of the inlet air.) To derive the relation, ΔT_v was plotted against T_{v1} and a straight line drawn through the points (Figure 19). The distribution of the points around the line is independent of the flow rate. The line corresponds to the equation:

$$\Delta T_v = (61.1 \pm 1.6) - 0.685 T_{v1} \quad (14)$$

This value for ΔT_v was substituted in equation (2) as follows:

$$\begin{aligned} \Delta \bar{H}_v'/t &= (W_v/t) k_v(\Delta T_v) = 3.63 (W_v/t) \Delta T_v \\ &= (W_v/t) ((222 \pm 6) - 2.49 T_{v1}). \end{aligned}$$

Figure 18 was constructed from this equation.

Figures 17 and 18 permit the estimation of steady state heat surplus, and of approximate ventilating air temperatures and flow rates, within the limitations mentioned. If heat is supplied according to these charts, no heating or cooling of the hands and feet is needed. The requirements for the head are not included in the nomograms, for reasons set forth in Section III-B. It is probable that the addition of at most a half a pound of air per minute would suffice for the head at the extremes of the temperatures given.

C. The Control Points.

The preliminary report (6) suggested that the primary sensing device be in the ambient air. Such a location would require, as previously pointed out, manual adjustment of its setting for various clothing combinations and activities. In other words, location in the ambient air would allow automatic response only to a part of the stress, and not at all to physiological strain. For conditions where temperature changes are likely to be rapid and extreme, and where men are likely to wear different clothing and be variously active, it is now suggested that there be two primary sensing devices: one, responding

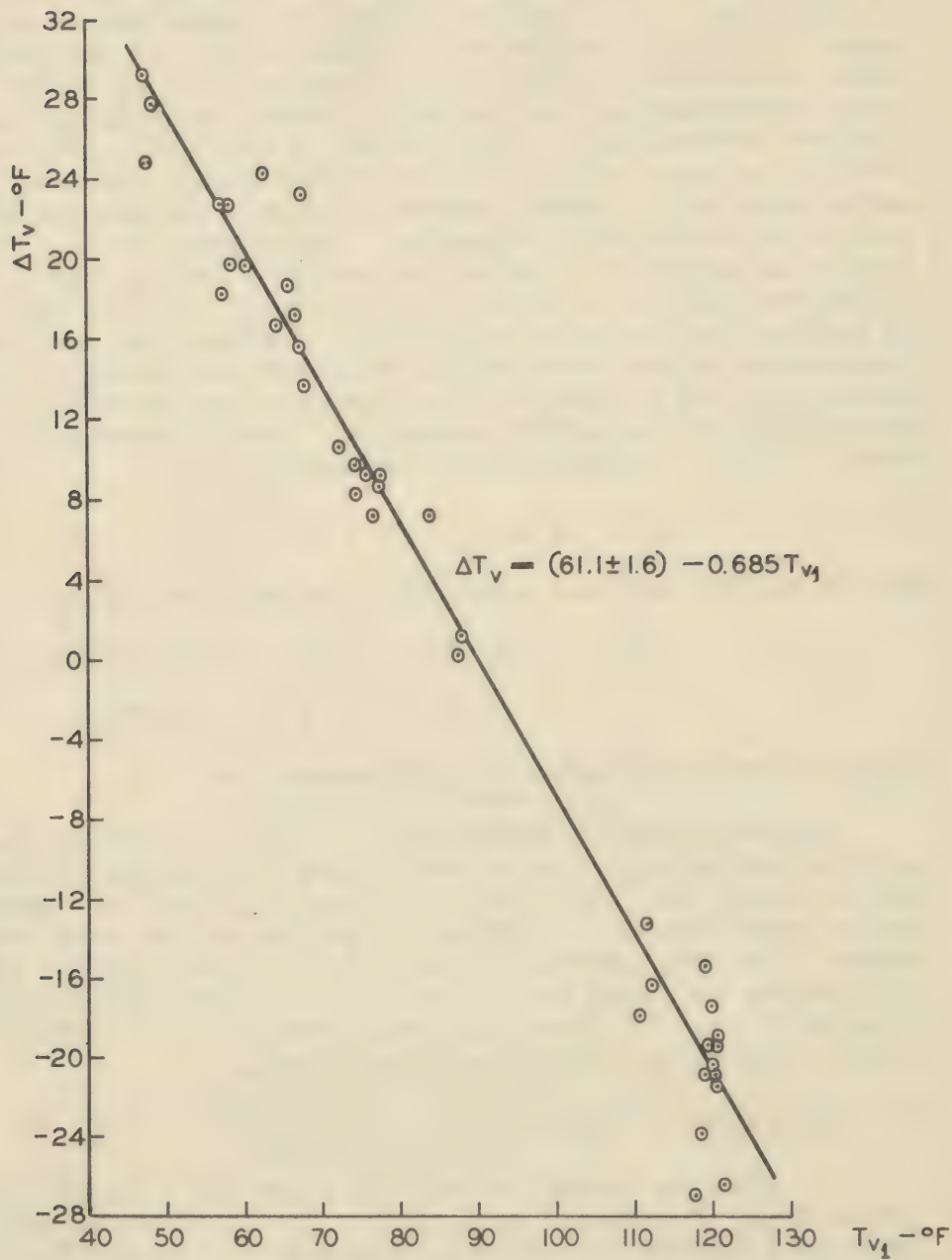


FIGURE 19

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to the temperature difference between the barrier coverall and the operative temperature, $T_c - T_o$ (8); and the other, to the actual barrier coverall temperature. The difference $T_c - T_o$ partly determines the rate of heat leakage through the clothing; the level of T_c apparently is an indicator of comfort. (More experiments are needed to establish the latter relation.) Our experience so far has been that T_c should be 86 to 88° F. when the ambient temperature is higher than about 60° F., and 93 to 95° F. at lower ambient temperatures. Control of $\Delta H_v/t$, through changes of air flow and/or temperature, should be such as to keep T_c at either of these two levels. Variation of activity and of outer clothing would be compensated automatically. Secondary control points would be the inlet air temperature and the flow rate. It is obvious that either the control point for T_c or for T_o , depending on the circumstances, may be omitted when the ambient conditions are fairly constant.

D. Notes on Equipment Design.

The air supply and distribution tubes must not kink; therefore the ratio of wall thickness to internal diameter must be relatively large. However, the tubes should be as small and light as possible. To meet both these conditions, the harness should operate at relatively high pressure. (An alternative, possibly lighter system would be thin walled tubes with restrictions at the distal ends. Back pressure would inflate the tubes.) To preclude discomfort from hot or cold air impinging upon the skin, diffusers should be provided at the distribution tube openings.

If the ventilating air is to leave the clothing through openings on or near the trunk, the distribution tubes to the legs should end about half-way down the calves; those to the arms, about half-way up the forearms. If the air from arms and legs is to escape from the jacket and trouser cuffs, the tubes should end just below the shoulders and at the upper thigh; and the overlying barrier coverall should be constricted around the shoulder and thighs. The trunk is the most difficult area to ventilate properly. A single inlet opening is not sufficient, and spacers are almost certainly required, especially if parachute harness is worn. Whether or not a special air outlet opening is necessary will depend on the neck opening.

In short, the problem of adequate heat supply at extreme temperatures is the problem of distribution of the ventilating air over as much of the body surface as possible. This might well be most simply achieved for the limbs by flow toward the extremities. Some flow of ventilating air into gloves and boots might thus be possible, reducing stress upon the extremities. If an anti-exposure suit, with tight wristlets and anklets, is worn over the insulative clothing, the air from the clothing cuffs could be returned to centrally located valved outlets.

Distribution of the air to the "body" should be in proportion to the area served; i.e., about 24% of the air to the trunk, 25% to each leg and 13% to each arm.

The barrier coverall should be of air impermeable material, and could advantageously carry the ventilating harness. For special purposes the coverall and harness might be integrated with other protective equipment, such as the anti-gravity suit. If the coverall temperature is used as a control point, temperature sensitive elements must be distributed over it to give its average temperature. (These elements can be combined to yield an electrically averaged temperature from one pair of lead wires.) Presumably, a coupling between the harness inlet tube and the air supply tube could be designed to incorporate suitable electrical connections. As noted in Section V-E, the minimum practicable insulation should be interposed between the air and skin. The greater the insulation outside of the air, the lower will be Q_g , and hence ΔH_v .

If engineering development is to proceed rationally, it will be necessary to determine the relationship between the air enthalpy change, and air flow and temperature for each experimental ventilating assembly--along the lines illustrated by Figures 18 and 19. (With physiological requirements established, most of the actual measurements can be obtained from copper man tests.) To arrive at these relations, it is a requisite that relative flow to the various body regions be measurable, as well as the air inlet and outlet temperatures. This should be borne in mind in the design of ventilating assemblies. It is likely to prove desirable to learn something about the distribution of the air within the assembly; perhaps this can be done by the addition of colored smokes to the ventilating air.

VIII BIBLIOGRAPHY

1. U. S. Patent 776,003. Body Ventilating Apparatus, No. 29, 1904.
2. Houghten, F. C., Ferderber, M. B. and C. Gutherlet: Cooling Workers in Hot Industry. Ind. Med. 10: 460, 1941.
3. Armored Medical Research Laboratory, Heat 1:
 - a. #9, Project 2-28: Test of Individual Crew Conditioning System. April 1943.
 - b. #16, Project T-2: Ventilation Requirements of a Ventilated Suit. Test of Heat Load Imposed by Protective Clothing. Sept. 1945.
4. National Research Council of Canada: Review of the Work of the Subcommittee on Protective Clothing of the Associate Committee on Aviation Medical Research, pg. 85, June 1946.
5. Marbarger, J. P.: Air Ventilated Clothing. Engineering Division Memorandum Report No. TSEAA-695-2FF, Dec. 1945.
6. Fetcher, E. S., Rapaport, S. I., Dorn, R. M. and Hall, J. F.: Requirements for the Internal Ventilation of Clothing, Preliminary Report. Engineering Division Memorandum Report No. TSEAA-696-105C, April 1947.
7. Gagge, A. P., Burton, A. C. and Bazett, H. C.: A Practical System of Units for the Description of the Heat Exchange of Man with his Environment. Science 94: 428, 1941.
8. Gagge, A. P.: Standard Operative Temperature, A Generalized Temperature Scale Applicable to Direct and Partitional Calorimetry. Am. J. Physiol. 131: 93, 1940; and Standard Operative Temperature, in Temperature: Its Measurement and Control in Science and Industry. New York, p 544, 1941.
9. Hall, J. F.: Thermal Insulation of AAF Flying Clothing. Engineering Division Memorandum Report No. TSEAA-696-105, Oct. 1946.
10. Burton, A. C.: Insulation of Ambient Air and Cooling Effect of Moving Air, in Clothing Test Methods, Washington, D. C.: 37, 1945.
11. Moritz, A. R., and Henriques, H. C. Jr.: Studies of Thermal Injury II. The Relative Importance of Time and Surface Temperature in the Causation of Cutaneous Burns. Am. J. Path. 23: 695, 1947.
12. Heating Ventilating Air Conditioning Guide, New York: 49, 1945.
13. Burton, A. C.: Human Calorimetry II. The Average Temperature of the Tissues of the Body. J. Nutrition, 9: 261, 1935.

14. Randall, F. E.: Articulated Plastic Manikan Standards. Engineering Division Memorandum Report No. ENG-49-695-28, June 1943.
15. Pinson, E. A. and O. O. Benson: Problems Inherent in the Protection of Flying Personnel Against Temperature Extremes Encountered in Flight. J. Aviation Med. 13: 43, 1942.
16. Freeman, N.: The Effect of Temperature on the Rate of Blood Flow in the Normal and in the Sympathectomized Hand. Am. J. Physiol. 113: 384, 1935.
17. Abramson, D. I. and E. B. Ferris, Jr.: Observations on Reactive Hyperemia in Various Portions of the Extremities. Am. J. Physiol. 129: 297, 1940.
18. Ferris, B. G. Jr., Forster, R. E. II, Pillion, E. L., and W. R. Christensen: Control of Peripheral Blood Flow: Responses in the Human Hand When Extremities are Warmed. Am. J. Physiol. 150: 304, 1947.
19. Spealman, C. R.: Effect of Ambient Air Temperature and of Hand Temperature on Blood Flow in Hands. Am. J. Physiol. 145: 218, 1945.
20. Miller, M. R.: The Effect of Vasodilators and Vasoconstrictors on the Vascular Changes in the Rabbit's Ear, Rapidity of Body Cooling and the Rapidity of Freezing of the Ear During Exposure of an Ear to Cold. Air University School of Aviation Medicine, Randolph Field, Texas. Project #490, Report #1, June 1947.
21. Spealman, C. R.: The Relationship between Foot Temperatures and Amount of Insulation Surrounding the Foot Immersed in Cold Water. U. S. Naval Research Institute. Project #297, Report #2, 1944.
22. Lewis, T. and G. W. Pickering: Vasodilatation in Limbs in Response to Warming the Body, with Evidence for Sympathetic Vasodilator Nerves in Man. Heart 16: 33, 1931.
23. Roth, G. M., Horton, B. T., and C. Sheard: The Relative Roles of the Extremities in the Dissipation of Heat from the Human Body Under Various Environmental Temperatures and Relative Humidities. Am. J. Physiol. 128: 782, 1940.
24. Taylor, C. L. and J. F. Hall: Assessment of the Physiological Adequacy of the XF-3 Flying Uniform. Engineering Division Memorandum Report No. TSENG-49-695-2L, Feb. 1944.

IX LIST OF SYMBOLS

Symbols are made up of two or more of the following: A combination of a property symbol with a subscript (and a superscript) symbol. Thus, Q_b is the total sensible heat; Q_b' is the sensible heat from the body less the head; and \bar{Q}_b' is the standard sensible heat from the "body".

Capitals (Refer to Properties)

- A - Area
- C - Specific Heat at Constant Pressure
- H - Heat Content (Enthalpy)
- I - Insulation (Total Insulation)
- Q - Heat Quantity
- T - Temperature

Lower Case

- k - constant
- t - time

Subscripts

- a - ambient air
- b - body, sensible
- c - barrier coverall
- e - evaporation
- f - foot (boot)
- g - garment (clothing surface)
- h - hand (glove)
- m - metabolism
- o - operative
- r - rectal
- s - skin
- v - ventilating air

- 1 - inlet (initial)
- 2 - outlet (final)
- σ - steady state

Superscripts

- r - regional
- ' - "body"; i.e., without head
- " - trunk, arms without hands, and legs without feet
- * - assumed value
- - standard, from selected experiments, for Air Force Man

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